THE MUSICAL EAR

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BY

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It may be said that the nature of a sensation depends primarily on the peculiar characteristics of the (receptor) nervous mechanism; the characteristics of the perceived object being only a secondary consideration.

HERMANN VON HELMHOLTZ
(from a passage in his *Physiological Optics* descriptive of our senses and sensations generally)

PREFACE

THE application of science to the production of music, by the gramophone, the 'wireless', and the electrotonic organ, constantly calls the musician's attention to musical acoustics. If he takes up a text-book of sound he may find in it much that is interesting to him if he has had some training in science, but it will have little to tell him about music. It is possible for him to begin at the other end and, starting with music, to find out what he can learn about sound and hearing as a musician. For the reader who is not concerned to base his knowledge of sound on the properties of matter and the laws of dynamics, or to make a study of theories of sensation, such an approach opens a way into much unknown territory.

The seven essays in this book may serve to make him familiar, in advance, with some places he will reach on his journey. Each one deals with some subject of musical interest and introduces the reader to aspects of acoustics which bear on it. In such a treatment it is inevitable that there should be some overlapping, and that the reader who is not already familiar with musical acoustics should find that it leaves large gaps in his knowledge. But, after all, one's knowledge is developed very much by the method of the jig-saw puzzle; and when one has built up certain parts of the picture one has gone a long way towards completing the whole.

None of these essays, save that on the sounds of church bells, deals with the production of sound. The production of sound calls for study of the vibrations of sounding bodies, and in *Music and Sound* the author has attempted a non-mathematical discussion of these vibrations which may help the musician to understand them. The present essays are concerned with vibrations, in air, that reach the ear, and with the response they set up in the ear. Discussion of this response involves some examination of the problems of aural perception which were excluded from *Music and Sound.* While, to that extent, the present book is complementary to the earlier one, it is self-contained, so far as it goes, and does not assume preliminary study of acoustics.

The reader of a book on acoustics is almost sure to meet, in passages dealing with music, some reference or allusion to a dictum of the 'theoretician' against whom Helmholtz

warned us in a passage quoted at the head of the first essay. This book is no exception; for the 'theoretician' refused to be excluded altogether from its pages. Perhaps it may be as well to allow him to appear and explain that he finds his premisses anywhere but in the history and practice of music; and if one of the best known of nineteenth-century writers on musical theory has been selected as spokesman for his fellows, the reason will be found on p. 5.

While the first object of these essays is to introduce the musician to a branch of science which has many applications of interest to him, they have a further and more far-reaching intention. The musician is only concerned with music as he perceives it through his sense of hearing. The vibrations in air which affect his ear are interesting only in so far as they influence his aural perceptions; and, as these essays will show, we have a great deal to learn about our aural perceptions. So much theory about musical acoustics has been at cross purposes with the art and practice of music that musicians are rightly impatient of it. The fault lies with 'theoreticians' who ignore the problems of hearing. The remedy lies in beginning with music. For an understanding of musical acoustics some acquaintance with counterpoint is more important than a thorough knowledge of sound as a branch of physics. We must start with correct musical premisses, and this is the note on which these essays begin and end. When the last, the most important, of them has been reached, the reader will find it useful to know certain facts of acoustics that emerge from each of the earlier ones; and he will realize how much of the territory that lies between music and acoustics has still to be explored.

Four of these essays have already appeared much in their present form in musical journals: the first in *Music and Letters*, the second in *The Musical Times*, the third in *The Musical Quarterly*, and the fourth in *Musical Opinion*. They are here reproduced with the ready assent of the editors of those journals, for which the author expresses his cordial thanks.

The author desires to record his indebtedness to Professor Dayton C. Miller for four traces of sound-curves, reproduced in this book, which were made with the phonodeik. Having read a draft of the second of these essays, Professor Miller was good enough to record, specially, to illustrate it, the two traces of the sounds of organ pipes reproduced in Fig. 4, Plate I, facing p. 14. Later he very kindly made the

harmonic analysis of these traces which is shown graphically in Fig. 5. He also supplied the two traces shown in Plate II, facing p. 56, which are not unlike those he published in *The Science of Musical Sounds*. The author also owes a debt to Dr. Robert H. Thouless for valuable guidance given to him in the elementary discussion of some problems of aural perception which will be found in this book. Finally, the author wishes to express his thanks to two firms of bell-founders, Messrs. John Taylor & Co., of Loughborough, and Messrs. Gillett & Johnston, Ltd., of Croydon, for the ready assistance they gave him in checking and completing the technical details of their craft mentioned in the fourth essay.

LL. S. LLOYD

GERRARDS CROSS

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I

INTONATION

We must distinguish carefully between composers and theoreticians. Neither the Greeks, nor the great musical composers of the sixteenth and seventeenth centuries, were people to be blinded by a theory which their ears could upset.

HELMHOLTZ, Sensations of Tone

An animated intonation (on the violin) is just as little mathematically true as an animated time-keeping is strictly according to the metronome.

HAUPTMANN, Letters[1]

The subject of just intonation is fatally fascinating to people whose mathematical insight has not attained to the notion of approximation. In art, as in mathematics, accuracy lies in estimating the relevant degree of approximation rather than in unrolling interminable decimals.

SIR DONALD TOVEY, Encyclopædia Britannica, 14th ed. (art. 'Harmony')

IF we measure the diameter of a penny, the value of the answer will depend on the accuracy of the measure used. We might measure the penny by the housewife's tape-measure. We should be able to give the result to perhaps a sixteenth of an inch. Or we might use an engineer's steel rule. That would give us an answer to at least a sixty-fourth part of an inch or, we might say with fair certainty, to a hundredth of an inch. If we used calipers with a vernier attached, we could estimate the measurement to a thousandth part of an inch. But it would be possible to make a measurement still more accurately by using optical means, when our answer would be expressed in wave-lengths of light. (There are more than forty thousand wave-lengths of yellow [sodium] light in an inch.)

The only instrument which the musician has for measuring musical intervals is his ear. As a measuring instrument the ear has its natural limits of accuracy, just like the various means described for measuring a penny. The accuracy of the ear depends on circumstances, such as the time allowed for making the measurement or the nature of the interval to be measured. No theoretical conjectures about acoustics and music are of any significance unless they take these limitations of the ear into account.

Four ways of measuring a penny have been described. The first three, by the tape-measure, the steel rule, and the calipers with vernier, may be compared to the varying

[1] From a translation in *The Philosophy of Music*, William Pole.

measurements of musical intervals made by the ear in listening to the performance of a musical composition. They indicate the accuracy of hearing which the art of music accepts as fixing the conditions it has to meet. The fourth set of measurements, using optical means, may be likened to the efforts of 'theoreticians' who, leaving the ear out of account, make calculations of musical intervals as heard in an imaginary world of their own. That is to understate their offence. The tuner of a keyboard instrument, with time at his command, and with power to control the rates of the beats he hears, can make measurements which we can liken only to our fourth way of measuring a penny. That gives to the calculations of 'theoreticians' a certain plausible appearance which makes them the more dangerous.

Crossword puzzles are a pleasant leisure occupation, but they are not literature. Jig-saw puzzles are an amiable diversion for many, but they are not art. There is entertainment in calculating the arithmetical niceties of the diesis, the diaschisma, the great limma, and so forth. The occupation is harmless so long as we remember that it has very little to do with music.

We are so conscious of the delicacy of the musical ear for detecting playing or singing out of tune that it is difficult to realize that its measurements are only approximations, and that their accuracy depends on circumstances. That this must be so can perhaps be more readily appreciated by thinking of other powers which our ears possess, or rather do not possess. Take, as an example, the ear's estimation of loudness. Loudness, as an attribute of sound, is perceived through a sensation in our ears. The sensation has a physical cause—the energy of the vibrations falling on the drum of the ear, which the physicist calls the intensity of the sound. Intensity is a physical measurement which is independent of the ear. (The physicist says that it varies as the square of the product of the amplitude and the frequency of the vibration in the air.) Now here is the surprising discovery of the laboratory. While the highest note we can hear vibrates only a thousand times as rapidly as the lowest note we can hear, it is found that, in the region above the stave with a treble clef in which the ear is most sensitive, the loudest note our ears can bear to hear vibrates with ten million million times as much energy as the faintest note they can hear at the same pitch. The figure is staggering;

but it prepares us for learning that when two high treble notes are sounded in succession with a short interval between them (half a second suffices) the ear can detect no difference in their loudness until, broadly speaking, the intensity of the sound of the second note shows a 25 per cent. increase over that of the first. Nature cannot have it both ways. The enormous range of intensity between sounds we can just hear and those which are unbearably loud demands a compensating sacrifice. That sacrifice is the sensitiveness of the ear to smaller changes of intensity than those described above. If, however, the notes are sounded without any interval between them, and under ideal laboratory conditions, the ear can detect loudness-intervals about half the size of those described.

This digression will be instructive if it serves to suggest that there *must* also be limits to our perception of differences of intonation, even though our ears are much more sensitive for pitch-intervals than they are for loudness-intervals. Any analogy with loudness-intervals will apply to notes heard in succession; and, in fact, the accuracy with which the ear estimates musical intervals in varying circumstances, melodic or harmonic, is not uniform. The three methods of measuring a penny with which we began were compared to the estimation of intervals in the actual performance of music. The full story is expounded by Helmholtz in his classical treatise, *Sensations of Tone*, and elsewhere.[1] Those who follow up the reference will find a full examination of the physical data which enable the ear to detect mistuning through beats between the harmonics and (if the notes are loud) the combination tones. This gives a physical scale of definition of musical intervals between notes sounded together. The octave is most sharply defined. Then as we proceed up the series of intervals with ratios between numbers progressively larger and larger, we find the definition becoming less and less. The edges of the interval, so to speak, become more and more blurred, till finally with the tritone the ear has no physical means at all of estimating exact tuning. (The physicist says that an octave is the interval between two notes whose rates of vibration are in the ratio 2/1. Theoretically the corresponding ratio for the fifth is 3/2, for the major third 5/4, for the minor third 6/5, and for the tritone 45/32.)

[1] See pp. 22 to 24.

We may compare the measurements by the housewife's tape-measure to the accuracy with which the ear estimates, or perhaps we should say is content to estimate, the position of *unessential* notes, the sort of accuracy which, as the context shows, Moritz Hauptmann had in mind in the quotation at the head of this essay, in which he was writing of decorating notes, such as 'passing-notes'. The measurements by the engineer's steel rule we may liken to the estimation, by the ear, of the intervals of discords. The measurements by the calipers and vernier may be compared to the accuracy which the musical ear expects in the intonation of the purest concords sounded on the strong beat of the music. This will not appear unnatural if its bearing on counterpoint is considered.

While it is important to remember that conjecture about intonation cannot ignore the varying sensitiveness of the ear in varying circumstances for what, to the 'theoretician', are small errors of intonation, there is another test which musicians must apply—and they have a right to insist on its application by the physicist. That test is the evidence of the history of musical composition. This is the rock, as Helmholtz warned them, on which 'theoreticians' come to shipwreck. And they received a complementary warning from one of our greatest physicists. In his Rede Lecture, Clerk Maxwell wrote: 'Helmholtz, by a series of daring strides, has effected a passage for himself over that untrodden wild between acoustics and music—that Serbonian bog where whole armies of scientific musicians and musical men of science have sunk without filling it up.' Subsequent investigations have shown us how to step round some of the puddles over which the German Colossus, as Clerk Maxwell called him, strode in his 'seven-league boots'. But if we let go of his coat-tails we shall assuredly founder in the bog.

It is not difficult to illustrate the danger of neglecting the history of musical composition in theoretical conjecture about acoustics and music. The English translation of Helmholtz's *Sensations of Tone* contains numerous interpolations and footnotes, as well as a lengthy appendix, furnished by his painstaking and erudite translator, Alexander J. Ellis. They are all carefully distinguished from the authentic text by square brackets. Ellis refers to the difficulties he experienced when first he studied the subject. Determined that others should not suffer in the same way, he attempted to make Helm-

holtz's meaning more clear to those who needed assistance. It is a pathetic fact that, by so doing, in this country he stood in the way of a true understanding of the master by his generation. Ellis had two disabilities. To him, as to his contemporaries, the music of the sixteenth century was a closed book. We have no such excuse. Further, he conceived of the musical scale as confined to the filling of the octave by a number of 'notes' of rigidly fixed intonation. To explain departures from that picture he invented 'duodenation' (a kind of musical nightmare). But he was only carrying to their logical conclusion the misconceptions of an academic school of music which saw truth in Dr. Day's artificial theories of harmony. For such a mistake there is no apology to-day. Those of us who cannot read German owe a great debt to Ellis for an authoritative translation of the *Sensations of Tone*. The full title of this work runs on: 'as a *physiological* basis for the theory of music'. The italics are the present writer's. Rameau's ideas, developed by Dr. Day, had a purely *physical* basis. That is why it is so dangerous to talk about the physical basis of music: one is all the time creating an atmosphere of misconception which excludes the ear from the picture.

If we understand why Ellis was misled, it is not unkind to demonstrate his mistakes. It would be easy to exhibit his footnotes and additions in a manner which would leave musicians convinced of his errors. Rather let us treat them as affording logical proof, by the method of *reductio ad absurdum*, that, when tested by the evidence of the history of musical composition, his musical premisses are found to be wrong. For instance, in his Appendix XIX to *Sensations of Tone*, Ellis gives an example of what he called 'trioni' music. He begins with the closing strain of a chorale from Bach's *St. Matthew Passion*, quoted by Helmholtz (see Chapter XV, page 471 of the 1875 English edition). This is in B minor and, as Stanford explains at the beginning of his *Musical Composition*, the second- and seventh-degree notes of the minor scale are typical mutable notes.[1] Bach uses a chromatic seventh on the supertonic to introduce his final cadence, and in this the major sixth of the scale must clearly be sharpened for ideally perfect intonation.[2] It, too, becomes

[1] i.e. notes whose intonation must be adjustable for different concords (see p. 73).
[2] See p. 73.

a mutable note. Ellis's 'trioni' music requires three harmoniums for correct 'duodenes'. (The reader who meets these terms for the first time need not worry about them—they do not exist outside Ellis's nightmare.) These harmoniums have pitches at intervals of a comma.[1] Ellis transcribes the extract from the *Passion* for these three harmoniums. Those who can turn up the result, page 684 of the 1875 English translation of Helmholtz, will see three notes each of which is common to two harmoniums. These notes are the mutable notes, C♯, A♮, and G♯, which we should expect to find. So far, so good, though Ellis is assuming an exact intonation some part of which, in fact, is lost in the limitations of the ear's accuracy. But now turn to his comments on the intonation of these notes to be found on page 470. '*It is evident therefore that Bach is thinking in tempered music.*'[2]

If this is true it must apply equally to earlier 'trioni' music. Opposite (Fig. 1) is the opening strain of 'Sumer is icumen in', transcribed from Grove's *Dictionary of Music*, to which the date *circa* 1240 is authoritatively assigned to-day.

For this example of Ellis's 'trioni' music Harmonium I is tuned a comma sharp on Harmonium II, which is tuned to the 'just intonation' of the theoretician,[3] while Harmonium III is tuned a comma flat on Harmonium II. In the second and fourth 'bars', to use modern terminology, we find harmonies with the second-degree note of the scale (here G) as bass; and these are the harmonies in the scale of F major which require mutable notes if the interval G to D is to be a perfect fifth.[4]

Three harmoniums are required for this 'trioni' music. '*It is evident therefore that*' *John of Fornsete, monk of Reading, thought in tempered music in the thirteenth century*—though Salinas

[1] A comma is the small interval by which a major tone exceeds a minor tone (as shown in Fig. 27, p. 70).

[2] Ellis had no doubts (see pp. 7 and 69) about the temperaments in which, as he imagined, Palestrina and Wagner thought. Presumably he wrote of 'tempered music', in the passage quoted, because he was uncertain whether Bach thought in the mean-tone temperament of his organ or the equal temperament of his clavichord.

[3] i.e. a theoretical conception of the scale with fixed intonation, that gives, with mathematical truth, the pitches required for tonic, dominant, and subdominant concords. To the musician, on the other hand, 'just intonation' means the playing or singing of the intervals of concords in tune, with ideal accuracy; and this requires a scale with flexible intonation for concords which produce mutable notes.

[4] See Figs. 27 and 28, pp. 70 and 71, for this interval in the key of C.

did not invent mean-tone temperament for more than another three hundred years. The conclusion might be contrasted with Ellis's reason for laying it down that Palestrina, 'often credited with just intonation . . . must have used mean-

Sumer is icumen in

circa 1240

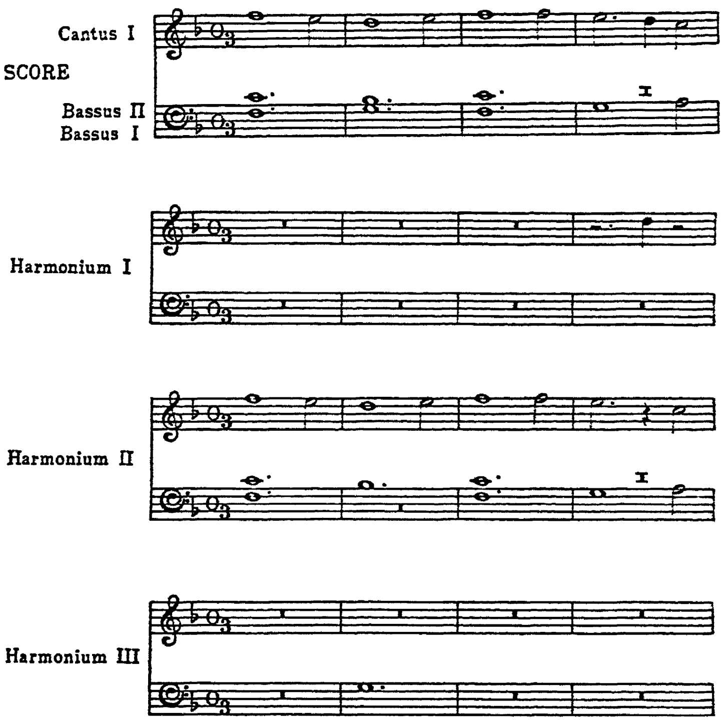


FIG. 1

tone temperament'.[1] But most musicians will agree that, following Euclid, we may continue: 'which is absurd; therefore the musical premisses were wrong. Q.E.D.' (The crochet on Harmonium I is particularly absurd, but not unfair to Ellis.)

Those of us who live in glass houses should not throw

[1] Because Palestrina [*c.* 1525–94] was junior to Salinas [1513–90]. The quotation is from a translator's footnote to the second English edition of *Sensations of Tone*, p. 351.

stones. It was because English musicians had forgotten their most glorious musical heritage in the nineteenth century, and because they accepted their counterpoint from Cherubini and their harmony from Dr. Day, that misconception arose among the physicists and that whole armies of English physicists and musicians alike have been lost in the Serbonian bog. We, who have not their excuse, should see to it that every one interested in the relation of acoustics to music shall know that musical scales can never be played perfectly on a keyboard instrument, because its notes are fixed, not mutable (though, on the clavichord, equal temperament was a good enough makeshift for Bach), that the scale system of the art of music is a flexible thing to-day just as it was in the sixteenth century,[1] that scales are developed by writing music, and that the art of music has never found any difficulty in using what some have described as an 'acoustically imperfect' scale: in short, that music is made by composers and not by 'theoreticians'.

[1] See p. 73.

NOTE.—The reader who may wish for further explanation of the intonation of 'Sumer is icumen in', as shown in Fig. 1, will find it examined in detail in the author's booklet *A Musical Slide-Rule* (Oxford University Press).

II

ELECTROTONIC ORGANS AND THE PHONODEIK

It is a commonplace of science that a long period usually elapses before a new discovery or idea finds practical application in industry. The scientific origins of the wireless set are to be found in the middle of the nineteenth century. It was then that Clerk Maxwell produced his conception of the electro-magnetic field, and that Joseph Henry exhibited electric oscillations of high frequency. From such pioneer work emerged the idea of electric waves, for which Hertz, a pupil of Helmholtz, subsequently gave an experimental justification. It is now forty years and more since Marconi secured his first British patent for wireless telegraphy; but it is only in recent years that musicians have gathered the fruits of all this patient scientific work. To-day they can listen in their own homes to the finest orchestras playing a concert programme. If they possess a television set they can even see, by wireless, something happening miles away as though it were happening before their eyes.

In 1843 Georg Ohm propounded the law of acoustics that vibrations in the air of the kind that he called 'pendular' are the only vibrations perceived by the ear as pure tones, and that all the varieties of quality in different musical sounds are the result of particular combinations of pure tones. Over seventy-five years ago Helmholtz published the confirmation, by his beautiful experiments, of the idea that the musical tone we hear is built up from a fundamental tone and a series of harmonic overtones, and that upon the selection, number, and relative loudness of these constituent pure tones depends the quality of the musical tone we hear, and that it depends on nothing else. Yet only in the last few years has the 'electrotonic' organ enabled us to hear synthetic music built up, in a manner for which Ohm first provided the theoretical basis, from vibrations produced electrically.

For good or ill this kind of music has come to stay. It may not be able as yet to produce all the tones we are accustomed to hear from familiar organ stops; that is beside the point. There is no theoretical reason why it should not do so. To musicians, unfamiliar with the scientific foundation on which 'synthetic music' rests, some simple demonstration of its principles may be welcome. Professor Dayton C. Miller

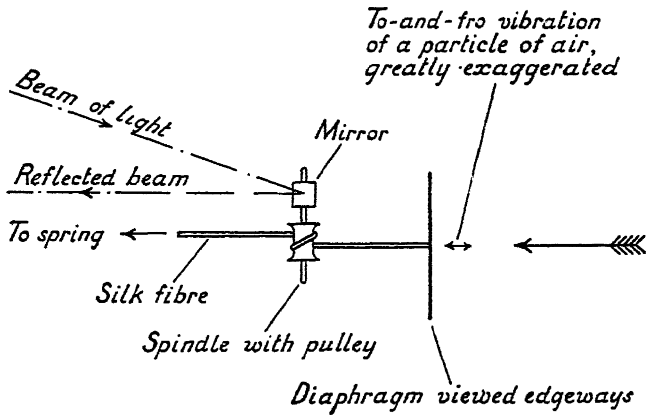
offers them such a demonstration with his phonodeik (φωνή = sound, δείκνυμι = to show). His treatise, *The Science of Musical Sounds*, was first published, in America, in 1916; and, like his more recent book, *Sound Waves, Their Shape and Speed* (1937), is full of information for the musician who wants to understand why an organ tone can be produced, electrically, without any pipes.

The phonodeik does not make a noise or sound a musical note. It is a kind of mechanical ear which has the power of drawing pictures of what it hears. In itself, the phonodeik is a very delicate piece of scientific apparatus. But for non-scientific musicians its interest lies in the fact that its mechanical principles are so simple and obvious that any one can understand them. Speak into a telephone; you set in vibration the diaphragm to which you speak. The vibration is carried electrically over telephone wires, and excites in turn, in the diaphragm of the receiving instrument, vibrations transmitted through the air to the hearer's ear-drum. Even if they could be made visible—as we might suppose, by illuminating a particle of air—the vibrations which go into the telephone would be far too rapid for us to perceive. We should merely see a minute bright line along which, in a manner characteristic, it may be, of a momentary sound, the particle of air would be vibrating at the rate of some hundreds of times a second. What a wonderful thought this really is! The behaviour of the particle of air, so vibrating, is precisely what enables our ears to tell us whether we are listening to voices, to a violin, an oboe, a trumpet, or an orchestra.

The phonodeik draws a sort of picture of the innumerable kinds of vibration which different musical instruments can produce. For the reception of the sound a diaphragm of very thin glass is employed. This diaphragm is set in vibration, like the diaphragm of the telephone, by a sound which falls on it. It is constructed and mounted so delicately that it vibrates, backwards and forwards, with the to-and-fro motion of the particles of air that press upon it. The problem which Dr. Miller had to solve was how to make visible the minute vibrations which musical sounds thus excite in the diaphragm of the phonodeik.

Here is where the resource of the ingenious experimenter, aided by skilled artificers, comes in. To the back of the diaphragm there is attached, at its centre, a delicate silk

fibre, the other end of which is held under slight tension by a fine spring. Between the diaphragm and the spring there is mounted, in beautiful jewelled bearings, a spindle on which there is fashioned a fine pulley. This should be pictured as of the size of the spindle of the balance-wheel of a good watch. Round the pulley the silk fibre is coiled,



The winged arrow shows the direction of the sound

FIG. 2. Diagrammatic plan of the phonodeik

once. As the centre of the diaphragm vibrates, the pulley will rotate first in one direction, then in the other; and its rotations will exactly reproduce the vibrations of the diaphragm. And already, in turn, the vibrations of the diaphragm will have reproduced the to-and-fro movements in the particles of air which lie against it, particles which first push the diaphragm in and then, so to speak, suck it out (Fig. 2).

How are we to observe the rotations of the pulley and spindle, remembering that they will occur at a rate of some hundreds a second, and that each rotation may be expected to be a complicated affair, not a simple, smooth, twisting backwards and forwards? Dr. Miller's answer is: by a spot of brilliant light, and a photographic film winding its way very rapidly across the region where the spot of light falls. To provide a spot of light he uses a pin-hole in an iron sheet held about an inch away from a brilliant arc-lamp.

The beam of light from this pin-hole is concentrated by a lens on to a tiny and very light mirror attached to the rotating spindle. As the spindle rotates the mirror rotates, the beam of light reflected by it moves up and down (the spindle is horizontal), and consequently the spot of light it produces moves up and down, just as the beam from an anti-aircraft searchlight can be seen to move by the motion of the blob of light it throws on the clouds. All that is needed is a sensitive film, capable of reacting to a very brief exposure (that is why the spot of light must be brilliant), and made to move horizontally as the beam waggles up and down. When the film is developed it will show the trace of the spot of light; the trace will appear white against a black background when printed as a 'positive'; and its shape will be that of a wave. It is quite easy to convince yourself of this. Take a sheet of cardboard and lay it on the table, holding one edge firmly in your left hand. In your right hand take a pencil with the point laid lightly on the cardboard. Now as you move the pencil steadily, away from and towards yourself in turn, draw the cardboard steadily from right to left, being careful that your pencil has a to-and-fro motion in a line at right angles to the motion of the cardboard. Then look at the wave you have drawn.

The particles of air move backwards and forwards along minute straight lines which point in the direction in which the sound is travelling. If they move with a steady, though rapid, pendulum-like motion, in very short swings (towards and away from the diaphragm), the diaphragm also will move with a steady pendulum-like motion; the spindle will turn smoothly backwards and forwards, like the axis in the neck of the familiar Chinaman modelled in porcelain and nodding his head; and the wave on the film will be a smooth curve. It will look like the curve in Fig. 3, Plate I.

If the particles move in a jerky fashion, sometimes halting or even turning back for a moment, so will the diaphragm move; so also will the spindle turn and the beam waggle; and finally the wave on the film will contain wavelets and kinks. In this way the film will show exactly how the particles of air are vibrating.

Even if we were enabled, by a kind of slow-motion process in the air, to see the to-and-fro motion of the particles of air when they are disturbed by a sound, we should not see any wave like that on the film. This always bothers a student

of music who, knowing little science, sees, in books on acoustics, curves like the waves on our film which are there described as sound-waves. And when the explanation is a mathematical abstraction, it is doubly perplexing to him.

There appear to be two ways of explaining the matter to him in a concrete manner. One is the somewhat laborious, but entirely convincing, way of drawing the actual motion of the particles along a line, and getting him to see what the result looks like. The other way is to picture the mechanical principle of the phonodeik. If the description given above enables him to do this, he will be on the way to understanding 'synthetic music' as never before. That is why musicians of an inquiring turn of mind, but with little mathematical attainment, are specially indebted to Dr. Miller. But they must always remember that the phonodeik substitutes up-and-down motion on the film for to-and-fro motion in the air. What Dr. Miller obtains are not real portraits of the sound-wave itself, but diagrammatic representations of them.

A tuning-fork, with its stem stuck into a resonance box, gives a practically pure tone. It produces a smooth, steady vibration in the air like that of a pendulum swinging through so short a distance that its motion is indistinguishable from motion along a straight line—a vibration which Ohm and Helmholtz called 'pendular'. The wave recorded on the phonodeik must therefore be quite smooth. In fact, it will be exactly like the curve drawn in Fig. 3, Plate I; and it is so represented in Plate I of *Sound Waves*.

Now this smooth curve is very important in the study of sound. If the reader has looked at its portrait, drawn in Fig. 3, and learnt to recognize its familiar features, he will no longer be alarmed at the label on which the scientist inscribes its name—'sine curve'. The reader should regard the name with the equanimity with which he reads 'quercus robur' on the label on an oak tree.

The next thing is to imagine this smooth curve much larger or smaller, as if viewed in turn through a reading-glass or through the wrong end of a pair of opera-glasses. Finally the reader should picture the curve, in various sizes, stretched lengthwise as if the paper on which it is drawn were elastic; and contrariwise, compressed as it would be if it could be squashed together from either end. Elongating

and compressing the curves in this way will alter their appearance. But it will not alter their essential nature. They will always remain 'sine curves'. The reader who imagines this series of changes in the original curve will have pictured all the different appearances of a 'sine curve'; and he will readily see how a simple wave can be made into a highly complicated one by imposing on it a whole series of wavelets, each of which might be labelled 'sine curve'.

Here is the key we are looking for to explain our 'synthetic music'. The 'sine curve' depicts a pendular vibration corresponding to a pure tone. All the wavelets due to other 'sine curves' depict different pendular vibrations corresponding to different pure tones. The shorter the wavelet, the more rapid is the vibration and the higher is the pitch of the corresponding pure tone. The more the wavelet moves up and down, the greater is the intensity of the vibration and the louder is the corresponding pure tone. The phonodeik, listening to the sound of a musical instrument, makes a complicated wave on the film; this complicated wave is a composite photograph, as it were, of pictures of many pure tones of different pitches produced by vibrations of varying intensities; and these are pictures which collectively represent the fundamental and the overtones in a musical note, and each one of them, by itself, would be a 'sine curve'.

Pictures made by the phonodeik of the sounds of different musical instruments, different organ pipes, or even the same instrument played *piano* or *forte* (e.g. the flute), or played in different ways (e.g. the violin), show that each has its own characteristic curve. Each curve contains the ingredients required to compound a musical sound of the desired quality —which is the objective of the electrotonic organ. When those ingredients have been determined the scientist has a specification to which he can work.

In Fig. 4, Plate I, there are reproduced the traces of the sounds of two organ pipes which Dr. Miller has made with his phonodeik. The upper one represents the sound of a gamba and the lower one that of an oboe organ pipe. In each case the pipe is sounding middle C. They illustrate in an admirable manner the way in which small 'sine curves', representing harmonic overtones, impose wavelets and kinks on a larger 'sine curve' representing the fundamental tone.

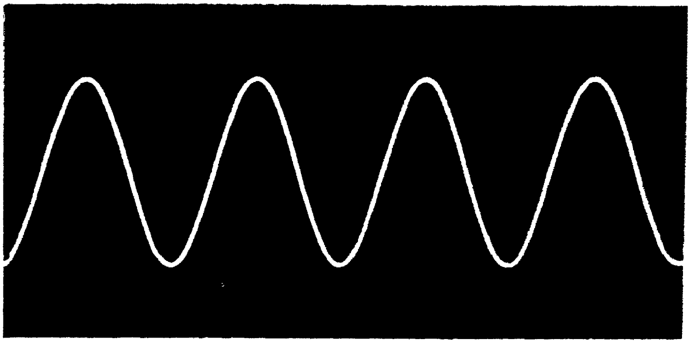
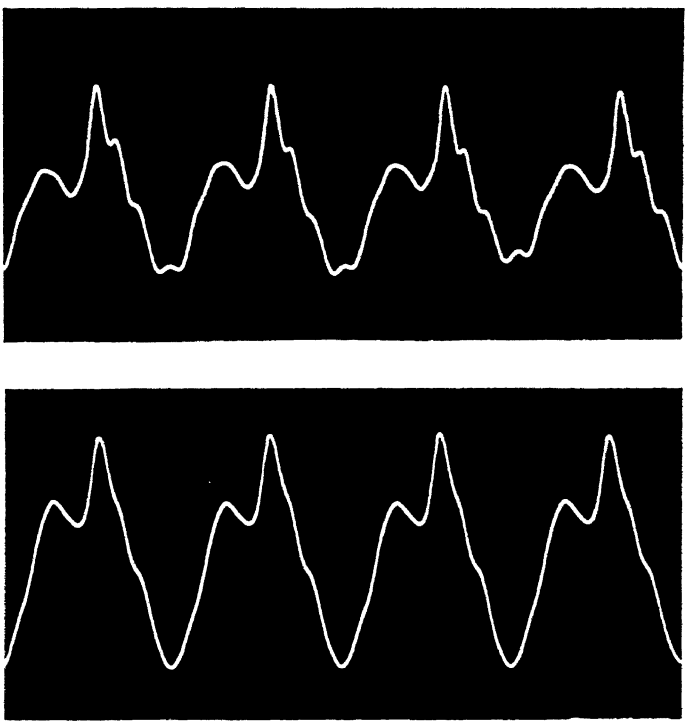


Fig. 3. Curve drawn to represent a pendular vibration



Dayton C. Miller

Fig. 4. Traces, representing the vibrations produced by organ pipes, made with the phonodeik

We have pictured a complicated sound wave as built up of a whole series of vibrations that can be represented by 'sine curves'. Such building up, or synthesis, is what the electrotonic organ does. But to obtain the specification required for this synthesis we have first to analyse, into its ingredients, the curve representing the desired musical sound. This converse process is quite within the powers of the scientist. He can do it mathematically; but he has invented a mechanical device to do it for him, called a harmonic analyser. Dr. Miller, using such an analyser, has determined the exact intensities needed by each of the harmonics (fundamental and overtones) to produce the different sounds of a number of different musical instruments. Some of his results are depicted, graphically, in *The Science of Musical Sounds*.

By means of such an analyser Dr. Miller has determined the relative intensities of the vibrations corresponding to each of the harmonics (fundamental and overtones) produced by the two organ-pipes whose sound-curves are shown in Fig. 4, Plate I. The results are depicted graphically in Fig. 5, which represents the relative intensities by the height of the series of circular marks (that surmount the several triangular black pointers where there is room to draw these).

The height of the circular mark for a particular harmonic is proportional to the percentage which the intensity of the vibration corresponding to that harmonic bears to the total intensity of the sound. These heights therefore tell us graphically what degree of intensity is needed by the vibration corresponding to each constituent tone if the final result is to sound like the notes of one or other of the organ pipes whose vibrations are recorded by the phonodeik: in other words, the specification to which the scientist can work to compound that note electrically. The harmonics are numbered serially, 1 representing the fundamental and 2, 3, 4, &c., the overtones. The distances between successive harmonics are drawn in the proportions needed to represent correctly the pitch intervals between them. It will be noticed that the intervals 1 to 2, 2 to 4, and 4 to 8, which are all octaves, are shown as equal.

The analysis of the vibrations produced in the air by organ pipes, represented simply by this graphical method, is the result of careful experiment and computation which

involved considerable labour as well as requiring most delicate apparatus to record the sound-curve and analyse it. George Ohm had at his disposal no such apparatus. Yet he was able to picture, in his head, the essential facts about the sensations produced in the ear by vibrations in the air

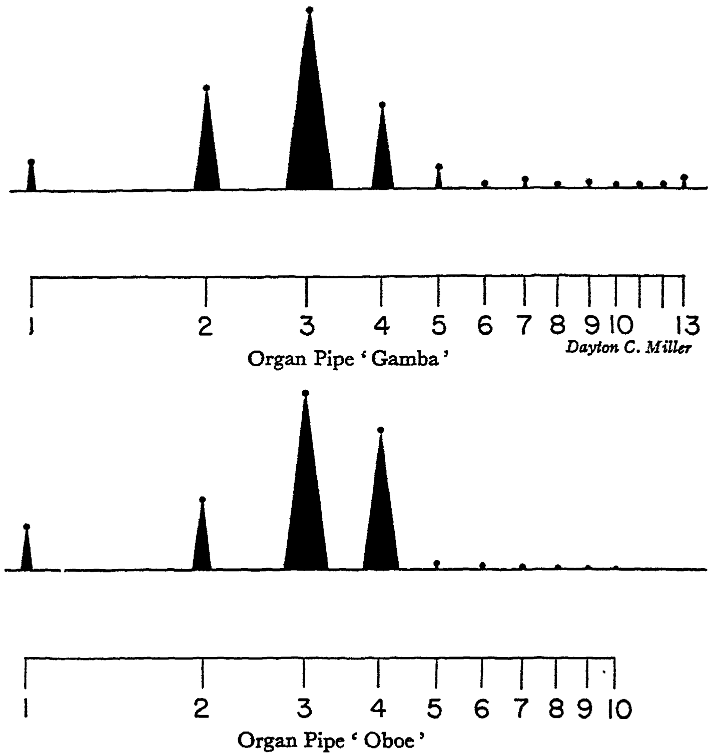


FIG. 5. Diagram, to show graphically the relative intensities of the several harmonic vibrations which produce the sound-curves in Fig. 4

which we perceive, not as vibrations at all, but as musical tones; and these essential facts we are beginning to apply, ninety years later, in the electrical production of these tones. As an effort of imagination and insight, his achievement is amazing; almost as amazing as the achievement of the musical ear itself, in analysing the vibrations by means of the aural sensations they excite, which we blend into the musical tone we perceive.

III

HERMANN VON HELMHOLTZ

If human beings had no ears there would be no music. Vibrating bodies would nevertheless conform to the laws of dynamics, they would still produce waves of compression and expansion in the air; flexible and uniform strings, and columns of air in pipes, would still vibrate with a series of simple harmonic motions whose rates could be expressed arithmetically as multiples of 1, 2, 3, 4, 5, &c. All this movement would go on just as it does now; but the sympathetic vibrations in our ears, which make it evident to us by means of audible sound, would be lacking. The whole of what some writers have called the physical basis of music would exist; but we should live in a world of silence, without music. When the human ear is introduced into this world, will it play no part in our consciousness of all this movement? It is surely inconceivable that the structure of our ears, and their natural properties, should have no effect on the sensations we derive from what, with a greater regard for exact terminology, we might call the physical *factor* in music. Think of the eye. There is light of so short a wave-length that it is invisible; yet this ultra-violet light, as it is called, produces a large part of the effect we record on a photographic film. We know that at the other end of the spectrum there are infra-red rays, but we cannot see them. The vibrations which produce visible light between these extremes are comprised in little more than an octave. Again, suppose that we first used a projector to throw a circle of green light on a screen, and then, in turn, used another projector by its side to throw a circle of red light on the same part of the screen. Now suppose both projectors to be switched on together. They would each throw the same light as before; no new kind of light would be added. But our eyes would tell us that there was now a new colour, yellow, in the circle. Consider, too, the so-called optical illusions, sometimes printed as curiosities in magazines. Clearly the structure and properties of the eye impose some natural limitations on our visual perception of physical facts. We are bound to assume that there are corresponding limitations on the power of our ears to perceive and compare sounds, even though they may be quite different from the limitations of

the eye in both nature and degree. To ascertain those limitations is the object of scientific inquiry which is of interest to musicians. Music exists in the minds of the composer and the artist, in the sensations in the ear of the artist and the listener, and in the perception of sounds, through those sensations, by their brains. It exists nowhere else; and its basis must be found there.

After all, correct premisses for a theory of music can never be evolved from scientific data. They are to be established only in one way—by study of the compositions of the great masters of the art from Palestrina and Byrd onwards. Not all writers about the relation between physical acoustics and music have served any apprenticeship to the practice of the art such as forms part of the training of any serious student of music. It is therefore hardly to be wondered at if some of these writers have reached conclusions which are at variance with centuries-old practice of composers. We must not then infer, as at least one of them has done, that composers have fallen into unscientific habits.[1] We can only conclude that the premisses of the theorist were wrong.

The words quoted at the head of the first of these essays (p. 1), 'We must distinguish carefully between composers and theoreticians',[2] were written, not by some composer poking fun at an untenable theory, but by one of the greatest men of science of the nineteenth century. It was Hermann von Helmholtz (1821–94) who showed what was missing in the conjectures of his predecessors about the relations between the science of acoustics and the art of music.

'Now whilst the physical side of the theory of hearing has been already frequently attacked, the results obtained for its physiological and psychological sections are few, imperfect, and accidental. Yet it is precisely the specially physiological part—the theory of the sensations of hearing—to which the theory of music has to look for the foundation of its structure.'[3]

The story was told by Helmholtz in *The Sensations of Tone as a physiological basis for the Theory of Music* (first published in

[1] Alexander J. Ellis; the English translator of Helmholtz's *Sensations of Tone*: '. . . That difficulty results from the habits of composers in systematically ignoring the difference of a comma between the second of any major scale and the sixth of the major scale of its subdominant.' English edition of 1875, p. 504, translator's footnote. The quotation illustrates, aptly, the difficulty which the translator made for himself by the faulty premisses discussed on pp. 6 and 7.

[2] *Sensations of Tone*, Eng. trans. of 1875, p. 345.

[3] Ibid., p. 5.

1862). It was his great achievement in this field to discover how the ear came into the picture, and to indicate what the physicist would call the limits of accuracy of the ear for estimating musical intervals in the conditions which obtain in the actual performance of music. He showed that physical acoustics was not enough. The aid of physiological acoustics, as exhibited by the human ear, is necessary to set the physical facts in their proper order of importance.

Helmholtz is one of the giants of scientific history. Qualified as a Doctor of Medicine, he became a professor of *physiology*, first at Königsberg (1849), then successively at Bonn (1855) and Heidelberg (1858). In 1871 he became professor of *physics* in Berlin, and seventeen years later he left this chair to become Director of the Physico-Technical Institute at Charlottenburg. He died in 1894. His contributions to science range from physiology to mechanics: among the earliest was his *Physiological Optics*; and in his later years his labours extended to the conservation of energy, hydrodynamics, electrical theory, meteorological physics, and the abstract principles of dynamics. He showed himself equally great in every field he entered. And the residual impression left, to-day, by reading his *Sensations of Tone* is this: had he had the opportunity of making himself fully familiar with the music of the sixteenth century, he would have anticipated, by about fifty years, the success of the efforts of musicians of a later date to get rid of a misleading theory of harmony.

That theory, carried to absurd lengths in England by Dr. Day, discovered a physical basis for music in the notes of what is called the harmonic series—notes to be found, for example, in the fundamental and the overtones of a vibrating string which is extremely flexible and quite uniform. This theory took its origin in the conceptions of Helmholtz's predecessors. In deriving their conceptions from the notes of the harmonic series, instead of indulging like the Greeks in metaphysical speculation, they were beginning to get on the right track; but because they left the ear out of account they were unable to arrange their evidence in any order of importance. Everything was in the foreground, so to speak. There was no perspective in the physical data assembled. For that reason they were led to faulty conclusions.

The fallacy of the theory, from the point of view of music, is obvious: it considered chords as things in themselves,

existing timelessly, with no reference to what had gone before, and little to what was to come after. It is as if the theorist had taken snapshots of music in motion, and had proceeded to study the results as still-life pictures; and this, so to speak, is just what the ear cannot do. Competent musical opinion urges the student to master harmony through counterpoint.[1] This opinion is founded in the history of musical composition. The procedures of that great harmonist, Johann Sebastian Bach, are to be traced without difficulty to their origin in the contrapuntal technique of the polyphonic period. But, were it necessary, this advice to the student could be reinforced by argument, equally valid, from physiological acoustics. Counterpoint, with its horizontal outlook, brings into technical study the effects of the physiological limits of the estimation of musical intervals made by the ear in the varying conditions which exist in the performance of a composition.

This digression, though it may appear to elaborate the familiar and obvious, is not uncalled-for if we are to understand how much of their studies Helmholtz's contemporaries would have had to unlearn before they could grasp the musical significance of his investigation of dissonance, definition, and the effects of mistuning. The artificial theory of harmony we have indicated, which in another form became the rules of thorough-bass, as it was called, held the field when Helmholtz's great work appeared. Academic musicians did not realize that Helmholtz's work, by exposing the fallacy of their conceptions, called on them to sweep aside a mistaken theory of harmony, as it has been swept aside to-day by their successors for musical reasons, and that it invited them to seek, in the study of music as it was and is, a sound foundation for the teaching of musical technique. All that remains of this theory to-day is a convenient set of what Sir Percy Buck has called nicknames[2] for familiar chords. Helmholtz himself did not presume to set the academic world of music right; but his acute mind and scientific insight left him in no doubt about the insecurity of the foundations on which then-current theory rested. 'I should consider a theory which claimed to have shown that all the laws of modern thorough-bass were natural necessities, to stand condemned as having proved too much.'[3]

[1] e.g. Stanford, *Musical Composition*, p. 22.
[2] *Unfigured Harmony*, p. 4.
[3] *Sensations of Tone*, Eng. trans. of 1875, p. xv.

The world with which we began, where human beings had no ears, is not so fanciful as it appeared. It resembles the world of musical theory which Helmholtz found. His *Sensations of Tone* excited tremendous interest. Books were written about it, lectures were given to expound it, some even ventured to commend to composers the importance of acoustics for the making of music—commendations which naturally fell on deaf ears. But few if any of his contemporaries appear to have appreciated the significance of Helmholtz's answer to the one question which interests the contrapuntist: How does the ear tell whether two notes are in tune? The student of counterpoint, regarding his musical material as consisting essentially of musical intervals, will find his interest in physiological acoustics quickened by learning that it provides an answer to this question. But it is not surprising to find that physiological acoustics made little impression on a world of theory unaccustomed to take the ear into account. 'Theoreticians' took off their hats to Helmholtz. They said 'How interesting', and straightway proceeded to talk, as before, about the physical basis of music. The phrase tends to maintain the misconception, which so troubled Helmholtz's English translator, that the art of music, like the tuner of a keyboard instrument, is confined to filling the octave with a number of 'notes' of fixed intonation. The corollary is the supposed existence of some mathematical imperfection under which the art of music must labour. So it might—in a world in which all ears were so different from our own that they would protest against a flexible scale and enharmonic change.

Physiological acoustics has been described as arranging the facts of physical acoustics in a proper perspective for the musician. Consider, for example, Helmholtz's investigation of definition in musical intervals, and his examination of the effect of mistuning them. Helmholtz begins with the sensibility of the musical ear. To the physiologist the reaction of the nerves of various senses, touch, sight, hearing, to the appropriate stimuli appears as a consistent whole. If the skin is scratched repeatedly by the finger-nail the response is much greater and more unpleasant than if the nail is steadily pressed on the skin. A light that flickers makes much more impression on the eye, and is far more annoying, than a steady one. The ear finds a beating tone disturbing where a steady one is quite acceptable. The unpleasant quality in

all these sensations is due to the intermittent character of the stimulus that produces each one of them. A physical beat in a musical sound is a flicker, as it were, in its intensity. If it is very slow it is by no means unpleasant, within limits: witness, for instance, the sound of the organ stop known as the *voix céleste*. As the beating becomes more and more rapid it becomes more and more irritating for a time; for a note in the treble clef, it does so till it reaches a rate of about 30 beats a second, corresponding more or less to the beating of two tones a semitone apart. After the rate of beating has passed this point it begins to be less unpleasant. Finally the sensation ceases altogether. At this stage it recalls the absence of flicker in a modern cinema. We know that, in the physical sense, the flicker is still there; but it is too fast for the eye to detect it. The sensibility of the ear to beats of different rates and intensities is the key to the problem: How does the ear tell whether two notes are in tune?

Helmholtz conceived the response of the ear to beating between the overtones of two notes as determining its appreciation of dissonance between the two notes.[1] This conception he applied to various musical intervals such as those set out, in musical notation, in Fig. 6, below. In this

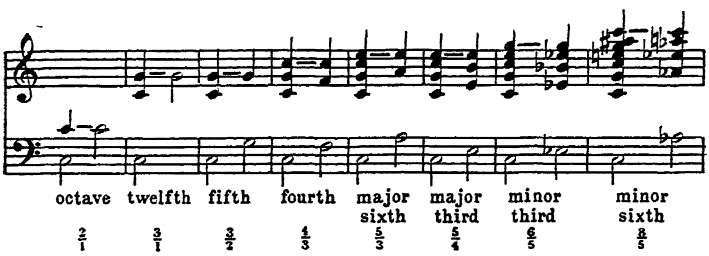


Fig. 6

illustration the prime or fundamental tones are represented by white notes. The black notes represent the overtones, which form the harmonic series with the prime or fundamental. They are continued in each case far enough up the series to reach a unison, shown by a thick horizontal line. With the interval between each pair of white notes is shown the ratio between the rates of vibration corresponding to the tones which form the interval. These ratios will be familiar to any reader of books on musical acoustics. Now

[1] A more detailed account of Helmholtz's theory of dissonance will be found in Chapters IV and V of the author's *Music and Sound*.

observe an interesting arithmetical fact. If the ratio is 3/2 we reach a unison between the third harmonic of one note (counting the white note as the first harmonic) and the second harmonic of the other note. If the ratio is 5/3 we reach a unison between the fifth harmonic of one note and the third harmonic of the other note, and so on. This makes it quite easy to picture the rate of vibration, and the intensity, of the harmonics that form unisons. Normally we may regard the harmonics as becoming progressively weaker and weaker as we ascend the series. At the same time, the vibrations become more and more rapid. Thus the third harmonic vibrates three times as fast as the fundamental; and the fifth harmonic vibrates five times as fast.

Now suppose the interval between any pair of white notes to be not exactly in tune. The unison between two of the harmonics of these notes, as shown in the illustration, will cease to be a unison. The two harmonics which ought to be a unison will beat perceptibly. If they are low in the series the beating will be powerful and will irritate the ear if it is fast enough. In any case the consonance, unless it is of the briefest duration, will be disturbed by the beating. On the other hand, if the mistuned unison is high in the harmonic series the beating, normally, is very faint. If it is sufficiently high in the series it will tend to become obscured by other dissonant effects. Any two tones a semitone apart produce unpleasant beats. Observe that, among the harmonics shown for the major third, the minor third, and the minor sixth, respectively, there are some a semitone apart. These will beat unpleasantly. As the harmonics are fairly high the beating may be faint; but it will be noticeable enough to obscure somewhat the beating of the mistuned unison.

This explains why musical intervals differ in their definition, as described on p. 4. The perfect concords, the octave and the fifth, are very sharply defined. The harmonics will protest very powerfully if there is mistuning. The imperfect concords, the thirds and sixths, will be less sharply defined. The protest of their harmonics against mistuning will be less effective. And we can readily imagine that in a discord such as the tritone (with a ratio 45/32) there is no definition. The interval is equally unpleasant whether exactly tuned or not. Its edges, so to speak, become quite blurred by dissonances. We thus see why enharmonic change, which is so puzzling when we think only of a physical basis for music,

becomes quite comprehensible when the musical ear is brought into the world of theory. In two closely related discords, in which the only difference is, say, that between F♯ and G♭, the slight alteration of the dissonance, due to beating between the harmonics, produces no very appreciable difference to the ear, which readily accepts the substitution of one slightly blurred outline for another.

Helmholtz's great work is to be read as a classic. The reader will then bear in mind that, when it was written, most of the English music of the Tudor period was buried in libraries or lay neglected on the shelves of practice rooms of cathedrals, and that a large part of Palestrina's compositions was almost as inaccessible, at least to any save scholars. As the effort of a mind of outstanding originality and thoroughness, blazing a trail into what was then unexplored intellectual territory, Helmholtz's work makes fascinating reading to-day, if studied with the eyes of counterpoint. But, as a classic, it should be studied as it left Helmholtz's pen, and without any contemporary glosses; so shall we remember that, in the more musical parts of his work, Helmholtz accepted as current doctrine the then-existing views of academic musicians which are rejected to-day by their successors.

To describe Helmholtz's work as a classic is not to say that it is the last word on the subject. It is an authoritative study of the physiology of the ear and the part it plays in our appreciation of musical sounds. In the quotation from its pages which was set out in the opening paragraphs of this essay, Helmholtz referred to two sections of the theory of hearing as demanding further inquiry, the physiological and the psychological sections. The knowledge which he made available set the first of these on a secure basis. Something has been done to fill the gaps in the second section; but much remains to be done before our knowledge of it is equally secure. It may then well happen that the distinction we naturally make between the sensation in the ear and its perception by the brain will prove to be too simple a conception to cover all the facts. Similar problems are presented by the eye and the brain as factors in visual perception. Dr. Thouless took this as the subject of his presidential address to the psychological section of the British Association at its meeting in 1938,[1] which he con-

[1] See *Nature*, 1938, **142**, 418.

cluded in these words: 'Let us hope that in the next twenty-five years, psychologists may be as successful in resolving the many remaining problems of visual perception as were the great Helmholtz and his contemporaries in making a scientific study of the sensory physiology of the eye.' If we read 'aural perception' for 'visual perception' and substitute 'the ear' for 'the eye', the hope is equally appropriate. In the attack on the problems of aural perception the evidence of the history of music should play its part. Musicians can help by ensuring a correct presentation of musical premisses; for, as Bernard van Dieren stated in the profoundly thoughtful and suggestive essay over which he inscribed, in place of title, the words *Sine Nomine*: 'The alleged problems of euphony that obsessed theorists solve themselves in well-balanced polyphony.'[1]

[1] *Down among the Dead Men*, p. 226.

IV

THE SOUNDS OF CHURCH BELLS

The art of change-ringing is peculiar to the English, and, like most English peculiarities, unintelligible to the rest of the world.... By the English campanologist, the playing of tunes [on a ring of bells] is considered to be a childish game, only fit for foreigners.... When he speaks of the music of his bells, he does not mean musician's music.... What he really means is, that by the English method of ringing with rope and wheel, each several bell gives forth her fullest and her noblest note. DOROTHY L. SAYERS: The Nine Tailors

EVERY student of musical acoustics learns that the notes of a musical instrument are not pure tones, but are built up from a combination of some of the notes of the harmonic series. The characteristic quality of each instrument depends on the selection it makes of these harmonics and on their relative intensities. What is it that so unquestionably distinguishes the music of bells from 'musician's music' produced by musical instruments?

The earliest systematic investigation of the sound of church bells was made by the late Lord Rayleigh.[1] A careful examination which he made of five tones ('partial tones',[2] as they are called) of each of the bells in a 'ring' of five in the church at Terling disclosed results very unlike those obtained with musical instruments. His analysis of the complex notes of these five bells may be represented *approximately* in staff notation as follows, the maker's name and the date being given above each bell:

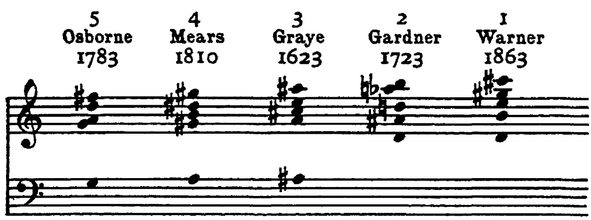


FIG. 7

[1] *Theory of Sound*, 2nd ed., § 234 onwards.

[2] To speak of 'partial tones', when we want to describe, collectively, the lowest or prime tone and the overtones, has two advantages: first, because counting is more logical if it begins with the lowest tone instead of with the first overtone (which is the second partial tone); and second, because the term is more comprehensive than the term we have often used, 'harmonics', since it covers both the prime tone and the harmonic overtones of musical instruments and the prime tone and the inharmonic overtones of, say, church bells.

Playing of the notes on the piano gives no representation of the sound of the bell, for each of these tones of the bell is a pure tone, whereas the notes of the piano contain overtones.

The positions, on the musical stave, of the first five tones of each bell are sufficiently unexpected. But still more surprising is the note given to a bell by the bell founder to describe its pitch : a note which he calls its strike-note. This is the note which would be assigned to a bell, when rung in a peal, by musicians who listened to it. For the five Terling bells the strike-notes are shown in Fig. 8. Observe that for

FIG. 8

only one bell, No. 4, are any of these strike-notes to be found among the tones of the corresponding bell; but each is an octave below the fifth tone of the corresponding bell. Is the pitch of the strike-note what is called, in popular phrase, an aural 'illusion'? This question will be discussed later. The answer is still subject to doubt; but no authority appears to think that the strike-note of untuned bells such as these exists outside the ear. What is in doubt is how far the strike-note is a subjective difference tone produced from two actual overtones by the unsymmetrical structure of the ear and how far it presents a problem in aural perception.

But apart from this nice point, the surprising thing is that out of each jangle of pure tones shown in Fig. 7 the ear constructs a musical effect at all.[1] Consider, too, what a tribute the facts pay to the medieval bell founder. He discovered by empirical means the design of bell which reduced the inharmonic jangle to inoffensive proportions. The art of tuning bells was practised by Francis and Pieter Hemony, famous Netherlands bell founders of the seventeenth century. Subsequently lost, it was rediscovered in this country in recent years. Tuning is achieved by rotating the inverted bell below a cutting tool, which can be used to remove metal as required. It is an art, like the voicing of organ pipes; and the skill of the tuner lies in removing the

[1] 'The dissonant effect of the inharmonious intervals actually met with is less than one would have expected from a musical point of view; although the fact is to a great extent explained by Helmholtz's theory of dissonance.' Rayleigh, 'On Bells', *Phil. Mag.*, 1890, **29**, 12 (i.e. inharmonious intervals between *pure tones* cannot produce beating of the kind described on pp. 23 and 24 for *complex tones* containing harmonics).

metal precisely where necessary to bring into some harmonious relationship all the five tones we have considered.[1] The bell, 'Great John', of Beverley Minster, dated 1901, is a famous example of the skill of the firm of John Taylor & Co. of Loughborough, by whom it was founded and tuned *exactly* to the following notes (as given in information kindly supplied by them):

FIG. 9

The same harmonious relationship of tones as that shown in Fig. 9 was produced in the largest bell ever cast in this country. It was made in 1928 for Riverside Drive Church, New York, by Gillett & Johnston of Croydon. It weighs 18¼ tons, and its note is C (in the bass clef), a major third below that of Big Ben. Its lowest five partial tones are therefore a fifth lower than the corresponding tones of 'Great John'. The five tones of the bell we have considered are regarded as the most important ones to tune; and the names given them, beginning at the bottom, are the hum-tone, the fundamental, the tierce, the quint, and the nominal. It is easy to understand that a method of tuning bells which produces a result such as that shown in Fig. 9 will make the sound of a bell sweeter.

Turn now to Fig. 7 again and compare the intervals in the tones of the five Terling bells with those just described. The bells which most closely approach modern ideals, or the perfection of a Hemony bell, appear to be Nos. 3 and 4; and the first of these, the oldest, was cast in the year of Byrd's death before the science of acoustics was born, thirteen years before Marin Mersenne's *Harmonie Universelle* appeared, and seventy-eight years before Joseph Sauveur published the notes of the harmonic series—a record for all time of the craftsmanship of the contemporaries of our Tudor composers.

It so happens that some quite simple experiments, which

[1] A diagrammatic section of a bell, showing the places from which metal is turned off to modify each of its lowest five partial tones, is given in *The Carillon*, Percival Price, p. 79.

any one can try at home, are all that is necessary to obtain a clear grasp of the principles of the complicated vibrations of church bells. Every one knows that a glass finger-bowl or a plain wine glass, tapped with the finger-tip or a lead pencil, emits a pleasant note of definite pitch. The same note is produced more powerfully by stroking the edge of the bowl, transversely, with a violin bow. But it can equally be produced, as most people know, by wetting the finger-tip and drawing it round the rim comparatively slowly, when the note rings out clearly. Many of us find it difficult to understand why the pitch of all these notes should be the same: for this must indicate a similarity in the vibrations in each case. The action of the violin bow provides the explanation. But first let us consider the effect of the blow from the finger or lead pencil, made from the outside of the bowl as we may suppose.

Consider what happens when a child's flexible wooden hoop is dropped on the floor from some height. The impact squashes the circular hoop into an oval shape. Exactly the same thing happens when the hoop is motionless and is struck by a moving object. Just as the momentum of the hoop previously caused it to become oval when it struck the motionless floor, so now its inertia causes it to become oval under the impact of the moving blow. What happens to the child's hoop happens to the rim of the finger-bowl when it receives a slight blow from something not too hard. The portion struck is, so to speak, pushed in. If it faced north, this inward bending there might be considered to squash outwards the portions facing east and west. These in turn will pull inwards the portion facing south. The flexural stiffness of the bowl seeks to restore the distorted rim to its circular form, but in so doing it overshoots the mark and produces another oval at right angles to the first. These ovals are exhibited in Fig. 10 on a *very* exaggerated scale. The rim keeps oscillating between these two oval forms passing in turn through every intermediate one, the middle position being the original circle. It does this until the internal friction due to bending, and the loss of energy due to the formation of sound waves in the air, bring the motion to rest. The meaning of the four short black lines in this figure, at N_1, N_2, N_3, and N_4, will be explained later.

How does this vibration resemble that produced by the wetted finger? Let us think of what happens when a violin

bow is drawn across the rim of the bowl. The behaviour of the violin bow, used on a string, has been studied very carefully, Helmholtz's investigations being classical, while among the more recent ones are those of Raman. The behaviour of the bow when used on the rim of the finger-bowl must be similar. The bow, made tacky with rosin, must seize the rim of the bowl (just as it seizes the string), and pull it outwards until the rim is so strained that it makes its escape from the bow's hold. Thereupon it swings back, passes through its position of rest, and moves inwards until its motion is almost (if not quite) exhausted. Thereupon the bow seizes it again, and the same performance is repeated. Speaking broadly, then, the vibration of the bowl when bowed is very like that produced by tapping it; but when the bowl is bowed the vibrations are maintained, when it is tapped they fade. The vibration in either case is like that pictured in Fig. 10.

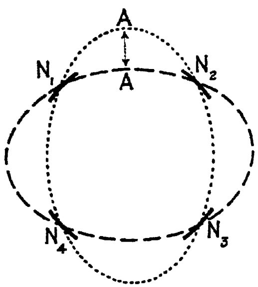


FIG. 10

Now consider the stroking of the rim with a wetted finger; not *transversely*, as when the bow was drawn across it, but along it, at right angles to that motion, in the direction of, say, a ruler held horizontally to touch the outside of the rim where stroked. The mathematician calls such a touching straight-edge or straight line a tangent, and he would describe the direction of this stroking as *tangential*—such a convenient word that we shall use it. Instead of a human finger, suppose the wetted finger to be that of a giant. It would be so large that we could imagine it as stroking always in the same place, instead of being drawn round the rim as our small fingers must be drawn to keep the sound going. The touch of the giant's finger would keep seizing a bit of the rim, which it would push in the direction of its own motion until the rim rebelled, escaped, rushed back, went too far, stopped, and was seized again by the touch of the giant's finger.

It might be supposed that this vibration would be very unlike the vibration in Fig. 10. In fact, however, it is very like it. Look at Fig. 10 and compare the lengths of the pieces of rim which lie between N_1 and N_2 in the two ovals. One is longer than the other. Since we may justifiably

assume that the stretching of the rim is negligible and that all we need envisage is its bending, this difference of length must mean that N_1 and N_2 are closer together when the oval lies from north to south than they are when it lies from east to west. In other words, N_1 and N_2 vibrate with the rim, and their vibrations are tangential as shown, diagrammatically, by the short thick lines. There is a point half-way between N_1 and N_2, marked A, where the rim is struck or where it is stroked by the bow. This point vibrates transversely, but it keeps in step with the vibrations of N_1 and N_2. It is marked in its two extreme positions. Thinking of the vibration as transverse, we call N_1, N_2, N_3, and N_4 *nodes*. The point A, and three others half-way between N_2 and N_3, N_3 and N_4, and N_4 and N_1, respectively, we call *antinodes*, to show that they always behave contrariwise to the nodes. We might think of the tangential vibration as the principal one, especially when it is the cause of the bowl's deformation, as we shall learn it is when we stroke the rim with a wetted finger; but as only a transverse displacement will disturb the air, and so produce sound waves in it, it is the transverse vibration we naturally think of as the principal one. It is certainly the natural one to think of when the bowl is tapped. But, whether we think, primarily, of the transverse vibration or the tangential one, we are thinking of exactly the same vibration looked at, as it were, from two different points of view.

Now replace the giant's finger with our own, which by reason of its small size must be moved round the rim. As it moves, the rim vibrates rapidly, and the point we are stroking becomes a node, vibrating tangentially, and constantly slipping away and being seized again as it was by the touch of the giant's finger. It does this so rapidly that it would hardly notice the relatively slow motion of the finger. But, in fact, the vibration of the rim has to move with the finger; and under the finger there is always a node, vibrating tangentially. We can convince ourselves of this by looking at the vibration of the surface of the water in the bowl. This surface has a pattern which slowly rotates with the finger.[1] This pattern becomes more obvious if the water is replaced by methylated spirit. We may think of the nodes and antinodes in the rim as a pattern which rotates with the finger.

[1] It is advisable to use a plain bowl made of thin glass of good quality; it should be half full of water.

The behaviour of the finger-bowl has been described at length because it is the key to the vibrations of a church bell. Rayleigh made an experiment to demonstrate the vibration of a finger-bowl which was so beautifully simple that it must be described for the benefit of those with a mechanical bent. (Other readers may skip this paragraph.) We saw that N_1 and N_2 vibrated tangentially, they had no transverse motion; but they vibrate in opposite directions to each other all the time. A, half-way between them, vibrates transversely but has no tangential motion. Intermediate points have a motion betwixt and between. At N_1 the motion is wholly tangential. The moment we leave N_1 in the direction of A, a transverse component creeps into the motion. As we go on this becomes greater and greater, while the tangential component becomes less and less. At A the tangential component disappears. Between A and N_2 the motions are mirror-images of those between N_1 and A. All the vibrations are at the same rate, and all vibrating points reach the ends of their swings together. We may therefore combine the motions for all intermediate points by the parallelogram law. It follows that the resultant motion will always be in a straight line. The vibrations will therefore be shown diagrammatically by Fig. 11 (in which the bending of the rim through 90° between N_1 and N_2 is ignored):

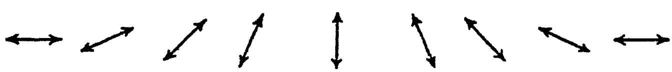


FIG. 11

Rayleigh's experiment showed his genius. His apparatus was extremely simple: a glass bell-jar with a small chip in the rim, a candle, a Coddington lens, and a wetted finger! He set the candle where its beam was reflected by the chip in the rim of the inverted bell-jar, which represented our finger-bowl. This gave a spot of light which vibrated when the rim vibrated; and its vibrations, always linear as in Fig. 11, were magnified by the lens and, being far too rapid for the eye to follow, they were seen as minute bright lines. The vibrations were produced by the wetted finger. As the finger moved slowly round the bell-jar, all the vibrations which lie between N_1 and N_2 of Fig. 10, then all which lie between N_2 and N_3, and so on, passed in turn through the bit of rim containing the chip. (Remember the rotating

pattern in the finger-bowl.) Rayleigh found that whenever his finger moved a quarter of the way round the rim the bright line seen through his lens turned completely round once, as in Fig. 11, which is just what would be bound to happen if his explanation, given above in popular language, were correct.

Let us now take an ordinary tea-cup, such as that pictured in Fig. 12. Tap the rim of the cup with the edge of a tea-spoon. When tapped exactly above the handle and at three other points (marked in Fig. 12 by arrows) which divide the rim into quarters, the cup gives a distinct note. When tapped at points halfway between those marked by arrows (shown in Fig. 12 by crosses) the cup again gives a distinct note, but a different one. The second note is sharper than the first—by a semitone on many cups, on some by as much as a whole tone. If tapped in between these eight positions the cup produces both notes, the one or the other sounding the louder as we alter the striking point. The result is a jangle. It is important that you should actually try this experiment, and not be content to read about it. It will make it much easier for you to understand what follows.

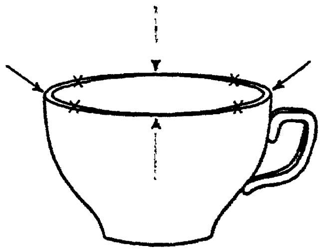


FIG. 12

The different vibrations of the rim of the tea-cup when struck by the tea-spoon are illustrated in Fig. 13. The circle on the left represents, diagrammatically, the vibrations when the cup is struck at any one of the points shown in Fig. 12 by arrows: that on the right represents the vibrations when it is struck at any one of the points shown by crosses. One such point of impact is marked, as an example, in each half of the illustration; on the left by an arrow, on the right by a cross. The handle of the tea-cup is represented by the shaded rectangle marked *H*. The nodes are all marked *N*, and the thick tangential lines at each node represent, on a very exaggerated scale, the nodal vibrations. The antinodes are all marked *A*, and the thick transverse lines at each antinode represent, similarly, the antinodal vibrations. The diagrams remind us that, when the cup gives a single note, the point of impact is always an antinode such as we found in discussing Fig. 10.

What happens to the tea-cup happens to a bell, if it is loaded at one point. A little weight can easily be attached to the bell, near its lip, with wax. The effect of loading the bell in this way is to lower the rate of its vibrations; but the rate of a vibration which is transverse at the loaded point is lowered more than that of one which is tangential there. In

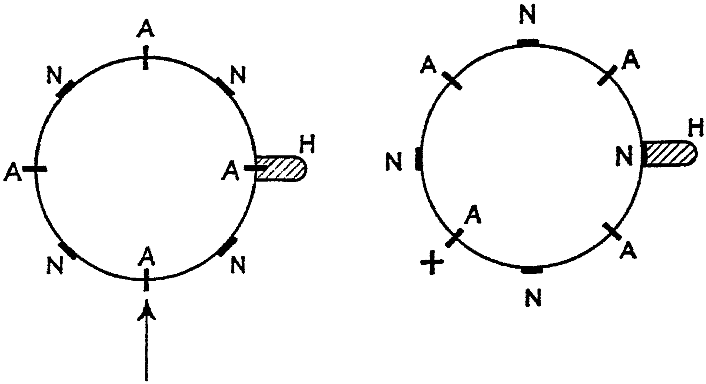


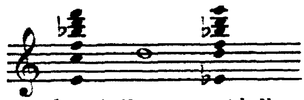
FIG. 13

our experiment with a cup we have a bowl loaded at one point, the load being the cup's handle. When we tap at the points marked by arrows, we excite a vibration in which the load moves transversely. This gives the lower note. When we tap at the points marked by crosses, we excite a vibration in which the load moves tangentially. This gives the higher note. A similar thing happens with a loaded bell. Tapping at eight more or less equidistant points, beginning with the point of loading, produces distinct notes, these points giving the higher or the lower note as we come to them in turn. But the loading of the bell being far less, in proportion, than the loading of the cup by its handle, we produce two notes very close together. When we strike the bell at points other than those giving a single note, we produce both notes and they give quite definite beats.

This was enough for Rayleigh; and by using these beats he was able to explore the more important vibrations of two church bells. One weighed 4 cwt., and one 6 cwt. They were by different English makers, but both were cast in 1888. Their first six tones were found to be approximately as shown in staff notation in Fig. 14. The pitch of both bells

was given by the makers as D, the note shown in Fig. 14 by the white semibreve. Rayleigh found that on each bell the fifth tone, beginning from the bottom, was an octave above this note; or, using the language of the physicist, we should say 'the fifth partial tone'.

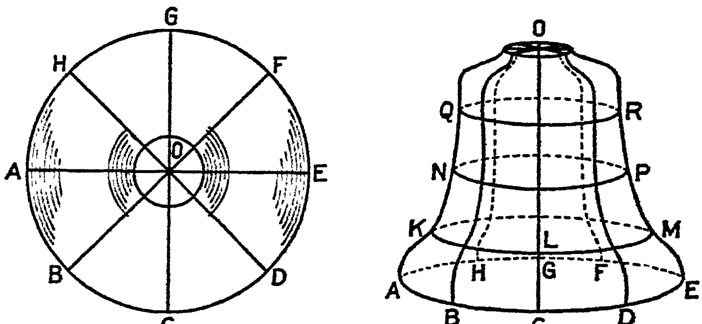
Rayleigh used suitable 'Helmholtz resonators'[1] to select and magnify the particular tone he wanted to hear, as pictured in Fig. 14, and to exclude the others; and by loading



6 cwt. bell 4 cwt. bell

FIG. 14

the bell at one point he produced beats in the selected tone, for reasons we have discovered. He then tapped round the bell along a series of circles of latitude. Fig. 15 is intended



Bell seen in plan

Bell seen in perspective

FIG. 15

to make the meaning of this clear. The circles which pass through the points marked *KLM*, *NP*, and *QR*, shown by black lines, and represented by dotted lines behind the bell, we may call circles of latitude. The lip itself, *ACEG*, is a circle of latitude.

Rayleigh began by picking out the deepest tone of the bell and examining the corresponding vibrations. He found, on every circle of latitude, eight points at which the beats in the tone he was listening to disappeared. Moreover, he found

[1] See *Music and Sound*, p. 102.

that all these points corresponded in successive circles of latitude; and each set of corresponding points lay on what we may call a meridian. These meridians are shown in Fig. 15. In the plan they appear as the lines *OA*, *OB*, *OC*, *OD*, *OE*, *OF*, *OG*, and *OH*. In the perspective we see five of them: the curved lines *OA*, *OB*, *OC* (which looks straight), *OD*, and *OE*. Three others are behind the bell. Two of them are shown by dotted lines *OF* and *OH*. The eighth one is *OG*, completely hidden behind *OC*.

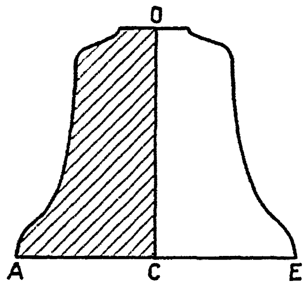


FIG. 16

It is much easier to understand what the world looks like if we can examine a globe, than it is to make it out from a map of the world in the atlas. If you have the slightest difficulty in making a clear mental picture from Fig. 15, here is a way to make it more concrete. Take any bell, say a dinner-bell, or any bell-shaped object, like an inverted flower-pot. On it mark all the circles of latitude and meridians shown in Fig. 15, and add the letters in their appropriate places. Use this instead of Fig. 15 in what follows.

The eight meridians discovered by Rayleigh, on which beating disappeared from the tone he was listening to, corresponded to the eight points on the rim of the tea-cup which give clear notes when tapped as described above. Just as the points on the tea-cup marked by arrows or crosses are fixed by the position of the handle, so the eight meridians on the bell are fixed by the point of loading, and one of the eight meridians would pass through it. The vibration of the lip and all the other circles of latitude would be as shown in Fig. 13. When he was tapping at one of the eight points on a circle of latitude he would produce an antinode there.

The nature of the bell's vibration, when tapped at one of the eight points that give no beats, is clear. Its surface is divided into four segments by four nodal meridians. Two of these segments are depicted in Fig. 16. Two others on the back of the bell would resemble them, and we should show the one on the left white and that on the right shaded. When the shaded segments were vibrating outwards the white ones would be vibrating inwards, and vice versa. The four segments are divided by meridians which vibrate tangentially,

the middle one, *OC* for example, vibrating from right to left and vice versa. These are nodal meridians. Down the middle of each segment runs a meridian which is vibrating transversely: these are antinodal meridians. One of them passes through the point where the bell was tapped without producing beats. On Fig. 15, or on our flower-pot, the segments would be the triangular areas *AOC*, *COE*, *EOG*, and *GOA*. The nodal meridians would be *OA*, *OC*, *OE*, and *OG*; the antinodal ones *OB*, *OD*, *OF*, and *OH*. The vibrations are illustrated in Fig. 17, in which Fig. 10 is adapted, for comparison with Fig. 16, with less exaggerated displacements and rotated through 45°.

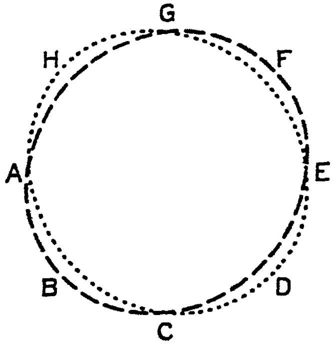


Fig. 17

Now suppose the load to be removed. The two notes which used to be produced—one of them when the tapping was at four of our eight points, the other when the tapping was at the other four—would be replaced by a single note. There would no longer be a distinction between the *rates* of the vibrations in the two cases; but the *nature* of the vibrations would be just what we found when the bell was loaded. When the bell is hung, the point at which the clapper strikes corresponds to a point at which it was tapped to produce the vibration shown in Figs. 16 and 17; and the clapper might be supposed to strike the bell on the meridian *OB*.

This description explains in outline the beautiful technique employed by Rayleigh. His equipment was of the simplest: a mallet to tap with, a load to produce beats with, and a Helmholtz resonator to pick up the desired tone with. The vibration we have described was that corresponding to the deepest tone of the bell, the hum-tone.

In the same way Rayleigh investigated the vibrations corresponding to four other partial tones of the bell. The second partial, called the fundamental (as already explained), also produced four nodal meridians, but a new effect was discovered as he tapped straight up the bell. At a point about a quarter of the way up the bell, the sound of the second partial, as picked up by the resonator, disappeared.

Similar points were found on other meridians, and they all lay on the same circle of latitude, which we may suppose to be represented by *KLM* in Fig. 15. This was therefore a nodal circle. The vibration which sounds the second partial divides the bell into eight segments, separated by the four meridians found for the hum-tone and the new nodal circle now found. Four of these segments are shown in Fig. 18, as they would appear on that part of the bell which was drawn as visible in its perspective appearance in Fig. 15. The other four segments are out of sight at the back, but they make a kind of chess-board pattern with the four shown in Fig. 18. If you marked an inverted flower-pot, as suggested on p. 36, to represent the circles of latitude and the meridians on the bell, you can easily reproduce this chess-board effect by making four of the segments white, with a piece of chalk. It will then be easy to see how the bell is vibrating. When the four red 'squares' are vibrating outwards (the shaded ones in Fig. 18 and two others at the back), the four white ones are vibrating inwards; and vice versa. Any segment which is next to the lip is always vibrating in the opposite way to the segment above it on the bell. If, therefore, we could look down on the bell, from above it, and imagine it vibrating with a kind of slow-motion, we should see that when the bottom quarter was deformed into one of the ovals shown in Fig. 17, the top three-quarters would be deformed into the other oval. Each part of the bell would vibrate as in Fig. 17, and each would always be vibrating in the opposite manner to the other. This vibration would bend the bell in more places than that of the hum-tone; and it is easy to imagine that the additional bending would be bound to make the vibration more rapid than that of the hum-tone.

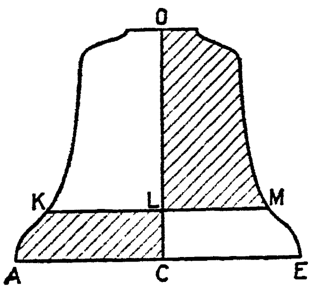


FIG. 18

Let us now return to Fig. 10, which we used originally to represent the vibration of a finger-bowl, but which we shall now think of as depicting the lip of the bell as we should see it if we were beneath it, looking up into its mouth. There were four nodes in the vibration there figured. But a vibration would be possible in which there were six nodes or even

eight or ten nodes. On each side of a node the segments of the lip are vibrating in opposite directions. Going round the lip, it bends, in, out, in, out, and so on. If we could imagine an odd number of nodes, this would be impossible, and at one of them the lip would have to bend through an angle, when it would, of course, crack. The flexural stiffness of the bell and its cohesion would prevent such bending. The nodes therefore always occur in pairs, and four is their least number.

Rayleigh found that the third and fourth partial tones both required six nodal meridians, for there were twelve meridians at which beating ceased, just as the prime tone, with four nodal meridians, produced eight meridians with no beating (for reasons discovered with our tea-cup). But the vibration corresponding to the fourth tone differs in some subtle way from that corresponding to the third tone, though no nodal circle was detected by Rayleigh. That there was a difference in the two vibrations was evident from the different way in which the intensities of each tone varied as he worked up the bell. For the fifth partial tone he found eight nodal meridians, with sixteen meridians at which beating ceased[1]. The importance of our study of the finger-bowl and the tea-cup for any attempt to picture the vibrations of a bell is clearly evident.

The five vibrations we have been considering, which correspond to the first five partial tones of the bell, cannot be excited singly by the clapper. But they are independent of one another, and each can be excited, as a resonance effect, by a pure tone of the same pitch. For example, if a tuning-fork, of the exact pitch of one of the partial tones of the bell, is set in vibration and held against the bell, at a suitable spot, it excites the appropriate partial tone, loudly, as a pure tone. There is nothing peculiar to the bell in this. The overtones of a plucked string are independent, and each can be excited as a resonance effect. In a flexible and uniform string they are harmonic; but if a string is loaded at one point, say by a drop of sealing-wax, its overtones become inharmonic, as are those of an untuned bell. Control of the overtones of a musical instrument by the fundamental is not

[1] Rayleigh used relatively small bells. More recent work with larger bells, which facilitate investigation of the upper partial tones, indicates a nodal circle for the third partial and one for the fifth partial, both about half-way up the bell, and one just above the soundbow for the much fainter fourth partial. A. T. Jones, *Phys. Rev.*, 1928, **31**, 1096.

universal, though the fundamental and the overtones of an organ pipe, for example, are linked through the periodicity of the eddy stream at the mouth. The possibility of tuning a bell lies in the independence of its partial tones.

When the clapper strikes the bell all its vibrations are excited together, and the total vibration of the bell becomes very complicated. (Readers who are not interested in mechanics may prefer to skip this paragraph.) It is not difficult to understand what must happen to any particular spot on the bell's surface. The explanation of the effect of several simultaneous vibrations on a particle of matter was first given by Huygens (1629–95), to whose inventive skill we owe the spiral spring of the balance-wheel of our watches. At any one moment the vibrations which produce one or more partial tones of the bell may be trying to bend outwards a particular spot on its surface, each by different amounts. At the same moment the vibrations which produce other partial tones may be trying to bend it inwards, again by different amounts. The spot on the bell's surface can only be in one place at a time, however; and, to find where this is, we add all the outward displacements and subtract from the total all the inward displacements. The answer gives the exact amount by which the spot is displaced outwards or inwards at the particular moment. In the same way we can picture a combination of the tangential vibrations of the spot on the bell's surface. To find the complete motion of the particular spot we must combine these transverse and tangential vibrations,[1] somewhat as we did those for two simple vibrations in Fig. 11, which we may now think of as representing the vibration of the hum-tone. Now, if you can, imagine all this going on, all the time, all over the bell.

The effect of loading a bell at one point has been described at length, because Rayleigh made such skilful use of it to examine the vibrations; but it has interest apart from this. The art of bell-founding declined with the passing of the master-makers in the seventeenth century, just as did the art of making violins half a century later. Bells of later date founded by the traditional methods of the middle ages not infrequently had some irregularities or inequalities in the thickness of their soundbow or elsewhere, and this produced

[1] Actually, the vibrations would not all have the same periods, as in the simple case of Fig. 11. The result would not be a straight line, but a complicated form of what are called *Lissajous' Figures*.

an effect of unequal loading. This is particularly true of large bells. Such bells exhibit beats.

The gongs of striking clocks are often not perfectly uniform in thickness, and this is equivalent to unequal loading. The consequent jangle of tones is not pleasant. But we now know that when the gong is struck at one of eight points on the circumference one or other of the principal tones in the jangle will not be excited, these eight points corresponding to the nodal or antinodal meridians found on a loaded church bell.

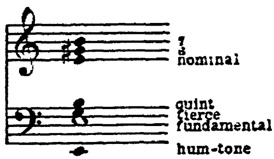


FIG. 19

That is why it is always possible to make the sound of the gong sweeter by twisting it round till the jangle becomes less offensive. When the bell is so twisted, the hammer strikes at one of these eight points, an effect which the reader can now explain to others by the tea-cup experiment.

Before we leave the discussion of the different modes of vibration of a bell which produce the first five partial tones, it will be useful to record the first *seven* partial tones of a very famous bell, since Hemony laid down the requirements of all these tones. He said that a good bell should have three octaves, two fifths, one minor and one major third. Ignoring small imperfections of intonation, these intervals are found in the Erfurt Bell, whose tones, as recorded by Starmer,[1] are given in Fig. 19. This bell was cast in 1497: it weighs 13¾ tons; and its diameter is 8 ft. 5¾ in. Starmer states that the hum-tone and quint are slightly flat, and the fundamental slightly sharp. Otherwise this bell exhibits intervals to which Hemony tuned large bells, whose sixth and seventh partial tones are audible, particularly the seventh. Professor Arthur Taber Jones, of Smith College, Northampton, U.S.A., whose modern work on bells and bell tones provides a fund of authoritative information, finds that the eighth, ninth, and tenth partials of a good bell are, as nearly as may be, successive notes of the diatonic scale. Thus for the Erfurt bell

[1] *Proc. Mus. Assoc.*, 1901–2, **28**, 32.

they would be C♯, D♯, and E in the treble clef. The first ten partial tones of a tuned bell therefore span three octaves, and provide two more tones than are found in this span in a series of harmonic overtones.[1] Observe, also, that the tenth partial tone provides the third octave which Hemony required of a good bell: striking evidence of his extraordinarily acute ear.

We have now examined the principal tones which go to make up the complete tone of a bell, and we have studied its vibrations. We have still to complete the picture by comparing the intensity and persistence of the various tones of the bell when struck, by the clapper, as it is struck in ringing with rope and wheel. The hum-tone is not very noticeable when the bell is rung in a peal. Its effect, then, may be thought of as rather like that of a 16-ft. bourdon added to the full swell of an organ. But it is the most persistent tone; and when the bell is tolled it may still be heard, humming sweetly by itself, when the other tones have died away. That it should last longest appears natural when one remembers that it requires the least bending of the bell into different segments.

The second tone is actually less intense than the hum-tone[2]; but in a bell that has been tuned, its pitch is the same as that of the loud-sounding strike-note, which explains why it comes to be called the fundamental; though the name is rather misleading to any one who thinks of the fundamental tone of a vibrating string or organ pipe as produced by its simplest mode of vibration. The third tone, the tierce, rings out clearly shortly after the bell is struck. The fourth tone, the quint, has much less intensity. The fifth tone, the nominal, is very important in a bell as rung in a peal. It is very prominent at first and, as its name implies, gives the note of the bell which is heard in a peal and therefore used by the bell-founder who hangs a 'ring' of bells. But it appears to suggest a note an octave below its own tone, as we have seen.

These characteristics of the tones of a bell are due to two things: first, its design, evolved by medieval craftsmen, which became a tradition; and, second, the point at which

[1] See Fig. 22, p. 54.

[2] For a thorough investigation, by modern electrical methods, of the position, intensity, and persistence of the first ten partial tones of four untuned bells, see A. T. Jones and G. Alderman, *J. Acoust. Soc. Amer.*, 1931, **3**, 297.

the clapper strikes the bell. Seen in vertical section, the shape of a bell may be represented diagrammatically as in Fig. 20.

The noticeable feature of the design is the marked thickening of the bell just above the lip in a region called the soundbow, at which it is struck by the clapper. The weight and rigidity thus added to this part of the bell must

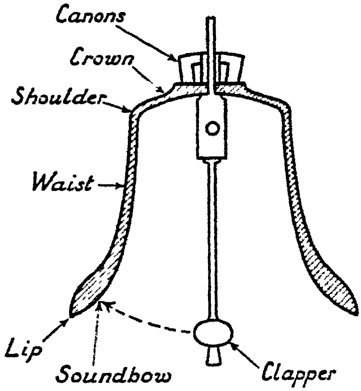


FIG. 20. Diagrammatic section of a church bell based, by kind permission, on a drawing by John Taylor & Co., of Loughborough

be controlling factors in its vibrations. It is interesting to note that the practice of the bell-founder makes the thickness of the soundbow about one-thirteenth or one-fourteenth of the diameter of the lip. 'Great John' of Beverley has a diameter of 7 ft. $2\frac{3}{4}$ in., and the thickness of the soundbow is $6\frac{1}{2}$ in. The bell weighs just over 7 tons 3 cwt. The clapper weighs just over 3 cwt. 'Great Paul' of St. Paul's Cathedral (1882) weighs $16\frac{3}{4}$ tons, and 'Big Ben' (1858) $13\frac{1}{2}$ tons.

Unless the bell is struck on the soundbow the complex tone we hear is altered in character. A bell struck in an unusual place would probably produce high partials of unusual intensity, and if the point of striking were half-way up the bell the hum-tone, also, would have unusual intensity.[1] Readers of *The Nine Tailors* will remember that the ex-convict Cranton, surprised in the church tower in circumstances which he had no desire to explain, sought refuge on the roof; and that in returning, when the coast was clear, he dropped his electric torch on one of the bells with terrifying results. In his own words: 'I'll never forget the noise it

[1] Rayleigh, 'On Bells', *Phil. Mag.*, 1890, 29, 8.

made. It wasn't loud, but kind of terribly sweet and threatening, and it went humming on and on, and a whole lot of other notes seemed to come out of it, high up and clear and close—right in my ears. You'll think I'm loopy, but I tell you that bell was alive. I shut my eyes and hung on to the ladder and wished I'd chosen a different kind of profession': a passage illustrating conspicuously the practical knowledge of bells which the authoress brought to the writing of the book.

But not only is it important that the clapper should strike on the soundbow, it is important that it should do so in the proper way, as when the bell is rung in a peal by rope and wheel. Unless it is so rung, a bell will not 'give forth her fullest and her noblest note'. The clapper, then moving in the same direction as the bell, overtakes it. There is a labour-saving device by which a rope, tied to the clapper, causes it to strike and jar against the stationary bell—a device which enjoys the contempt of all true bellringers. It must produce somewhat different vibrations, for it is liable to crack the bell. Readers of *The Nine Tailors* will remember that the original No. 2 bell, 'Carolus', 'was cracked in the eighteenth century, as a result of the abominable practice of "clappering" the two smallest bells for occasional services.'

Moreover, the material of the clapper matters. The usual heavy iron clapper produces the most sonorous and merry tone. In *The Nine Tailors*, when Sir Henry Thorpe died the clappers of the bells in the Parish Church of Fenchurch St. Paul were encased in leather buffets to ring a muffled peal. The upper partials would then have greatly diminished intensity; and the bells' softened notes would be characterized by their deeper and more solemn tones. In illustration, the reader may try striking a dinner gong, lightly, first with a hammer, then with a proper drumstick.

The remarkable phenomenon of the 'strike-note' of an untuned bell, judged by the ear to be an octave below the nominal, has always intrigued scientific investigators. Blessing discovered that it disappears when the thickening of the soundbow is turned off. But, as the Terling peal shows, Figs. 7 and 8, there is as a rule no actual tone of an untuned bell which corresponds to the strike-note. The strike-note cannot be picked out of the vibrations of such a bell by a resonator. Some have supposed the strike-note to be a difference tone, and recent experiments by Erwin Meyer and

Johannes Klaes have shown that, certainly on one bell, the difference tone of the fifth and seventh partial tones, which may lie somewhere in the region of the strike-note on many bells, is connected with it.[1] The strike-note and the fundamental can be made to have the same pitch by careful tuning, and are so made by the English tuner, to whom the terms are then synonymous. Otherwise the strike-note would only have the same pitch as the fundamental by a more or less lucky accident. Professor Arthur Taber Jones has recently investigated the subject again. His experiments, which are rather conclusive in their cumulative result, seem to show that, normally, the strike-note is a perceptual effect, derived from the nominal, an octave higher, and that the difference tone of the fifth and seventh partials probably has something to do with the creation of this perception.[2]

The story of the sound of a church bell is immensely fascinating in itself. To the musician, interested in the perplexing relations between physical acoustics and music, it tells something of the properties, limitations, and credulity of the human ear; and the contrast between the vibrations and tones of a bell, on the one hand, and those of a musical instrument, on the other, is such that each throws light on the other. That is why the sounds of church bells deserve more attention than they usually receive. For this reason, references have been given to original papers. In the paper on bells and bell tones, referred to on p. 41, which Starmer read before the Musical Association in 1901, there are two passages which provide food for thought:

'We must understand from the first that "tone" and "tune" are very different things. Good tone does not necessarily mean that a bell is in tune with itself or with others, and a bell may easily be in tune in the strictest meaning of the term, and yet of indifferent tone.'

'A less quantity of metal than is due to the calibre of the bell, produces a thin and unmusical tone. One reason why some old bells are superior to modern ones, is no doubt due to the fact that a greater weight of metal was used for the same note than is thought necessary now, on the ground of economy.'

When a bell is tuned perfectly, so that its first, second, fourth, and fifth partials fall into the harmonic series (the

[1] For an explanation of difference tones, as subjective effects in the ear, and of their positions in relation to the tones generating them, see *Music and Sound*, Chap. IV.

[2] 'The Strike-Note of Bells', A. T. Jones, *J. Acoust. Soc. Amer.*, 1937, 8, 199.

tierce is always odd man out), the musician would expect to find them blending in a musical tone whose quality would depend on the relative intensities of the corresponding vibrations. In turn these intensities would depend on the design of the bell and the weight of metal used. But, if his studies have taught him to think in terms of a *physical* basis for music, he would hardly expect that, given good design and sufficient metal, a bell whose tuning is imperfect may have a better tone than a perfectly tuned bell that is lacking in these desirable features. In reflecting on his perception of the quality of a bell's note he will remind himself that the partial tones of a bell are pure tones; and he will not think of the intervals between them as resembling corresponding intervals between the notes of musical instruments. The more he reflects on the sounds of church bells, and particularly on the remarkable phenomenon of the strike-note, the more doubtful will he become of theories of music which assume that our perception of musical tones gives a faithful picture of their physical causes.

V

THE NOTES OF THE HARMONIC SERIES

In the last part of my book, I have endeavoured to shew that the construction of scales and of harmonic tissue is a product of artistic invention. . . . The history of music shews us that the same properties of the human ear could serve as the foundation of very different musical systems. . . . In many cases we are still able to determine that the progressive changes in the tonal system have been due to the most distinguished composers themselves. HELMHOLTZ, Sensations of Tone

To the musician, listening to an artist or an orchestra, the music he hears consists of the perception of what he calls musical sounds by his ear and brain. One might sum up all scientific inquiry into the relationship between music and acoustics by describing it as the attempt to find out just what this sentence means. For all its apparent directness it is packed with question-begging terms. What is the distinction between the sensation in the ear and the perception of sound by the brain? Will it be possible to maintain this distinction as our knowledge extends? What is a musical sound? Is the criterion physical, sensory, or perceptual? What are the physical components of a musical sound? What part does aural perception play in selecting, disguising, and modifying the impressions produced on our senses by these physical components? Does music sound the same to different people? Why are some listeners more musical than others? It is not possible for any one to answer all these questions completely, and to some there are perhaps no answers at all as yet. We have a great deal to learn about listening, which we do with our brain as well as our ears. Now let us read the opening sentence again and consider how far its meaning was taken for granted.

In much that has been written about acoustics and musical theory, the physical causes of our sensations have been identified with our perception of them. This has resulted in misconceptions; and it may still mislead us if we are not careful. Consider, for example, musical pitch. Let us begin by reminding ourselves of the distinction we must make between the physical nature of a sound, the impression it makes on our senses, and our perception of the sound. Travelling through the air, a musical note takes the form of a complicated to-and-fro vibration of which we can draw diagrams by means of the phonodeik. When it reaches our

ears they discover partial tones in it; but these partial tones belong essentially to pure auditory sensation. Partly as the result of experience, partly no doubt through inherited powers, we blend these partial tones into a musical tone, of definite pitch, with a characteristic quality; this is a process of perception. Impressions on our senses are called *sensations*; the mental images of external objects or occurrences which we produce from them are called *perceptions*. Thus, we learn to perceive particular kinds of musical sounds as associated with the instruments that produce them; other kinds of sounds, containing different partial tones, are perceived as vowels.

Pitch, then, is a perceptual effect in our brains; and a musical interval is something recognized through our ears. No knowledge of science is required by a musician to enable him to understand what is meant by 'pitch' or by a 'musical interval'. When we begin to read about musical theory we begin to think of pitch as determined solely by the rate of vibration corresponding to a musical tone. We go on to picture an interval, in its physical aspect, as determined by the ratio of the rates of vibration corresponding to the two tones which form it. Up to a point we are right to do so, for we are thereby getting a clear idea about the most important factor in the sensation in our ears. But when we have done the arithmetic correctly we are no nearer to understanding *why* our ears say that any pairs of notes which have the same frequency-ratio produce the same musical interval. Nor must we unconsciously substitute the physical cause of the sensation for our perception of it through our senses. This is not mere verbal distinction. We have reason to think that pitch is not always determined solely by the rate of vibration corresponding to a musical tone, or 'frequency', as we call it, for pitch does not appear to be completely independent of intensity, or even of overtone structure. Men of science tell us that 'a change in the intensity of a musical sound, without any change in frequency, may give rise to a change in pitch. The effect is a maximum in the neighbourhood of 200 cycles per second [that is, a note vibrating 200 times a second, which is about A♭ at the top of the bass clef]. Below some 2,000 to 3,000 cycles per second an increase in intensity lowers the pitch.' The quotation is from a communication by Professor Arthur Taber Jones to *The American Physics Teacher*, June 1937, in

which references are given to original papers.[1] The phenomenon has been known for half a century or more. It was recorded, though not recognized as a perceptual effect, by Rayleigh.[2] Burton, using pure tones, detected flattening by a semitone or more at the pitch of middle C; and the amount varied with individuals. The effect is more complicated, and less marked, when harmonic overtones are present. These observations apply to pure tones or to musical notes sounded *separately*. They are not concerned with consonances, thus marking a difference between 'pitch' and 'musical intervals'.

Here is a definite distinction between the physical cause of a sensation and our perception of the cause. Realizing that such a distinction exists in this instance, one begins to suspect any musical theory which is derived solely from the physical factors in music and takes no account of any theory of hearing.[3]

To nothing in musical theory of the last century does this observation apply more emphatically than to conjecture based on what are known as the notes of the harmonic series. These notes have been made the starting-point of theories of harmony and of the scale which become grotesque when carried to their logical conclusions. We shall do well, then, to clear our minds about the terms involved. The notes of the harmonic series form a purely acoustical series; and, if we wished to be very precise, we should describe the series itself as an arithmetical series. To relate the notes of the scale to this series directly is mere fancy. We must turn to Helmholtz's work to discover how far notes of the series may play a part, indirectly, in our estimation of two tones as being in tune.[4]

The connexion between acoustical and mathematical harmonics may be traced to the discovery of Pythagoras that a vibrating string, stopped at two-thirds or one-half of its length, sounds the fifth or the octave of the note it

[1] C. V. Burton, *Phil. Mag.*, 1895, **39**, 447; H. Fletcher, *J. Acoust. Soc. Amer.*, 1934, **6**, 59; S. S. Stevens, *J. Acoust. Soc. Amer.*, 1935, **6**, 150; to which may be added H. Fletcher, *J. Franklin Inst.*, 1935, **220**, 405.

[2] *Theory of Sound*, 2nd ed., vol. i, § 67, p. 78.

[3] Since a musical interval is something perceived through our ears the precisian would object to the description, at the beginning of the first of these essays, of the ear as 'measuring' intervals, and would prefer the subsequent use of the more indefinite 'estimating'. We are now in a position to appreciate the nice distinction.

[4] See pp. 22 and 23.

produces when vibrating freely. A later Greek philosopher, Archytas (428–347 B.C.), an intimate friend of Plato, was probably the first to describe the numbers 1, $\frac{2}{3}$, and $\frac{1}{2}$ as being in *harmonic proportion*.[1] We notice that the reciprocals of these numbers are 1, $\frac{3}{2}$, and 2. Each differs by $\frac{1}{2}$ from its predecessor. Our original series in harmonic proportion might be extended to read:

$$1, \frac{2}{3}, \frac{1}{2}, \frac{2}{5}, \frac{1}{3}, \frac{2}{7}, \text{ and so on.}$$

This is a series which the mathematician, following the example of Archytas, calls a *harmonic progression*. The reciprocals of its several terms are:

$$1, \frac{3}{2}, 2, \frac{5}{2}, 3, \frac{7}{2}, \text{ and so on.}$$

Each term of this series differs by $\frac{1}{2}$ from its predecessor.

Here we find the origin of the term *harmonic series*, which is a mathematical term. The series:

$$1, \frac{2}{3}, \frac{1}{2}, \frac{2}{5}, \frac{1}{3}, \frac{2}{7}, \text{ and so on}$$

is a particular example of a harmonic progression. The harmonic series of acoustics is another particular example. It is a series of numbers whose reciprocals are all multiples of the reciprocal of the first number. If we begin with 100 vibrations a second, we get as this series of multiples: 100, 200, 300, 400, 500 vibrations a second, and so on; and the periods of vibration to which they correspond are:

$$\frac{1}{100}, \frac{1}{200}, \frac{1}{300}, \frac{1}{400}, \frac{1}{500}, \text{ of a second.}$$

Or if we think in hundredths of a second these periods become:

$$1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \text{ and so on,}$$

and each is the reciprocal of the terms in the series:

$$1, 2, 3, 4, 5, \text{ and so on.}$$

[1] The Greek conception of harmony (ἁρμονία) played its part in their philosophy. It had a much wider meaning than that with which we use the musical term; and our meaning does not apply to Greek music which was melodic. We echo the Greek meaning when we speak of people living together in harmony.

The peculiar virtue of the series:

$$1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \text{ and so on,}$$

lies in the periodicity which its terms exhibit. For example, a recurring quantity with a period denoted by $\frac{1}{3}$ (of any unit we like, say a hundredth of a second) recurs three times as often as one whose period is denoted by 1. But such quantities also recur, in groups of 3, exactly in the period denoted by 1. Recurring quantities with a period denoted by $\frac{1}{5}$ recur, in groups of 5, exactly in the period denoted by 1. Similarly, all the periods denoted by the several terms of our series recur, in appropriate groups, in the period denoted by 1.

This explains the acoustical connexion between the *harmonic series* of arithmetic and the *harmonic overtones* of a musical instrument. When we describe the overtones of a musical instrument as harmonic, we mean that while the fundamental tone in any note of the instrument vibrates once, the second harmonic (the first overtone) vibrates twice, the third harmonic vibrates three times, the fourth four times, and so on. It does not follow that all the notes of the harmonic series occur in the overtones of the instrument. Many may be lacking, and in no instrument are the vibrations corresponding to very high overtones sufficiently intense to be audible. If we drew sine curves (as explained on p. 13) to represent the vibrations of the harmonic overtones, they would produce wavelets when imposed on the sine curve that represents the vibration of the fundamental tone. The composite curve which the phonodeik could draw would keep repeating in waves of the same shape. Conversely, if the waves representing the sound of the musical note all have the same shape, the overtones in it must fall into the harmonic series. It is the virtue of most musical instruments that their overtones do not depart from the harmonic series to any discernible extent. Their overtones are then said to be harmonic. That gives to the instrument what we call a sweet tone. If the overtones of a musical instrument depart sensibly from the harmonic series they are said to be *inharmonic*. The sounds of an untuned church bell, or of drums, or of tuning-forks struck vigorously,

contain some quality that is jangling or rough. This quality is due to their inharmonic overtones. The sole judge of the quality of the note of an instrument is the musical ear. If the overtones of an instrument are harmonic, they blend so smoothly with the fundamental that we perceive the result as a single note of characteristic quality. *We may think of the harmonic series of acoustics as a kind of measuring-rod for testing overtones physically, and we must be careful not to think of it as anything more than this.*

A generation or more ago we were taught that to learn harmony we must study the manifestations of the fundamental bass. The theory on which dogma rested was found in the notes of the harmonic series, which had an irresistible fascination for 'theoreticians' who left the ear out of the picture. It was only natural, therefore, that there should be a theory of the scale, as its counterpart, which derived notes of the scale from the harmonic series. The curious will find, in Donkin's *Acoustics*, a detailed account of the making of 'artificial scales'. Donkin's comment is authoritative: 'This proposition is to be understood merely as a statement of a mathematical fact, and not as involving any theory of the actual derivation of the scale.'

When once we have gained clear ideas about notes whose periods of vibration fall into the harmonic series of acoustics, and when we are sure that they do not justify any arithmetical derivation of the scale, then, but not till then, it becomes useful on occasion to examine their relation to the musical scale. For example, this relationship has a practical importance in the electrical production of musical tones; and only the trained ear of the musician can decide how important slight departures from it may then be. Between the eighth and the sixteenth notes of the series there is an octave; and the harmonic intervals in this octave may be compared directly with the musical intervals in an octave of the diatonic scale. This comparison is exhibited in Fig. 21, in which vibrations whose periods fall into the harmonic series are shown in the centre. The intervals between them are drawn in the correct proportions, and they are denoted by the figures 8, 9, 10, . . ., 16, which represent the ratios of their rates of vibration to that of the first note of the series. This would be denoted by the figure 1, and it would be three octaves below the note marked 8. On the left-hand side of the figure these notes of the harmonic series are

compared with ideally tuned musical intervals which are all measured from the graduation marked 'zero'. These musical intervals, also, are drawn in their correct proportions.[1] On the right-hand side of the figure the notes of the harmonic series are compared, similarly, with a perfect

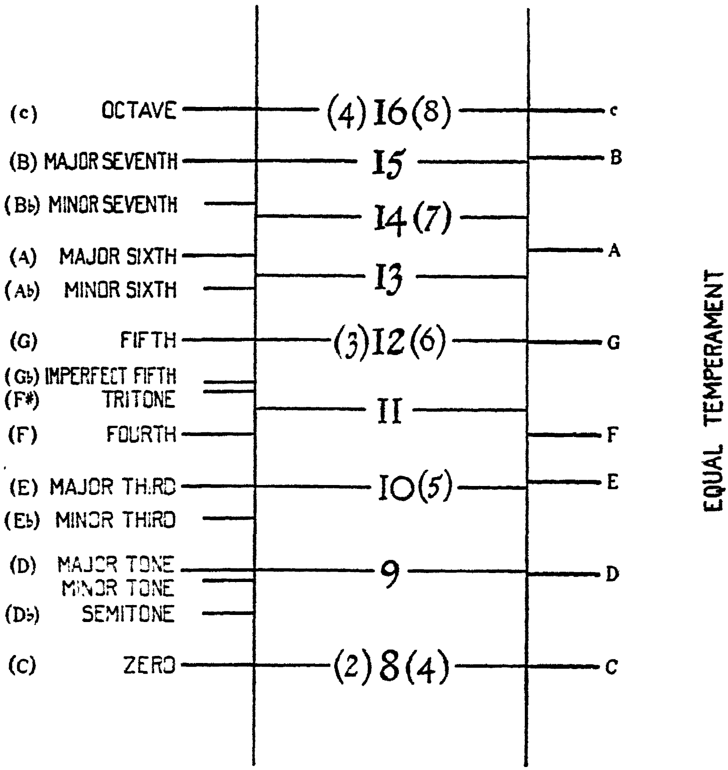


FIG. 21

tuning in equal temperament. The octave we have chosen will serve also to exhibit all the lower notes of the harmonic series. If we select only the evenly numbered notes, 8, 10, 12, 14, and 16, and divide their numbers by 2, which means

[1] The musical scale is flexible: see pp. 8 and 73; *Music and Sound*, p. 36; and *A Musical Slide-Rule*, p. 12. The 'scale' depicted in this figure, as shown in brackets on the left-hand side, gives the positions of notes required to produce exactly tuned concords on the tonic, dominant, and subdominant, see p. 72, and these concords are consonances defined by rates of vibrations which affect the sensations in the musical ear, see p. 23.

transposing them down an octave, we can compare the positions of five notes of the series whose numbers are 4, 5, 6, 7, and 8 with the musical intervals. These numbers are shown in brackets in Fig. 21. If we now select only the notes numbered 8, 12, and 16, and divide their numbers by 4, which means transposing them down two octaves, we can likewise compare the positions of three notes of the series whose numbers are 2, 3, and 4 with the musical intervals. These numbers are also shown in brackets in Fig. 21. Finally, if we select the notes numbered 8 and 16, and divide

FIG. 22

their numbers by 8, which means transposing them down three octaves, we have the first octave of the harmonic series, between the two notes whose numbers are 1 and 2. If we had space on the page, we could actually show all four octaves in continuous succession, much as the first ten notes of a series beginning with C in the bass clef are shown in succession, in a different way, on the musical stave in Fig. 22; but the arithmetical device just explained makes this unnecessary.

The seventh note of the series in Fig. 22 is shown by a black note for a reason which we can easily discover. We notice at once from Fig. 21 that the fourteenth note, and therefore the seventh note an exact octave below it, does not correspond to any note of the diatonic scale. What we may call the 'harmonic seventh' is smaller than the minor seventh by rather more than the difference between the major tone and the minor tone (which difference is called a comma). That is why the seventh harmonic of C was represented by A♯ in Fig. 6, p. 22, though even that note of the musical scale is slightly too sharp for the purpose. Music has not yet made use of the harmonic seventh as a definite interval of the diatonic scale. This is the point at which theories of the scale based on arithmetic go to pieces. A theory which proves too much stands self-condemned. Arithmetical theories of the scale produce, as

essential notes, those with ratios 4 : 5 : 6 and those with ratios 8 : 9 : 10. Logically, therefore, notes with ratios 6 : 7 : 8 should also be found in the scale. But, since the harmonic seventh is not to be found there, the premisses which arithmetical theory postulates must be wrong. The ear is not interested in arithmetic: it is only interested in its own sensations. The idea of an arithmetical derivation of the scale is fundamentally false. Scales have no existence apart from music, and they are produced in the attempt to make music. There is nothing sacrosanct about the European scales. In other parts of the world, scales for melodic use have been developed with intervals not found in European music.

We must never imagine that, to explain music, we have all we need in the science of acoustics. A notable illustration of this truth is afforded by the chord of the 6/4. Acoustically, this is the most consonant of the major or minor triads, but every student of counterpoint learns of it as a discord.

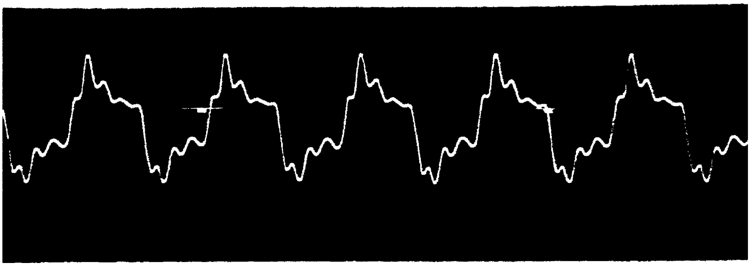
To return to the notes of the harmonic series, Fig. 21 also makes it evident that the eleventh and thirteenth notes of the series correspond to no note of the musical scale and produce with the fundamental, or its octaves, no interval used in the practice of music. The seventh, eleventh, and thirteenth notes of the harmonic series are sometimes spoken of, in a loose sense, as dissonant or even inharmonic. This is a confusion of terms. No note of the harmonic series can form a dissonance with the first note of the series, for its periods always recur exactly, in groups, in each period of the fundamental, and the two notes will always blend quite smoothly. To call these notes inharmonic is even worse; for it means that we are confusing 'harmonic', in the sense in which it applies to the notes of the series, with 'harmony'. It is true that notes of musical instruments which produced unisons with the seventh, eleventh, and thirteenth notes of the series would give, with similar notes for the octaves of the first note of the series, intervals which would tend to sound like discords played out of tune; but that is quite a different thing. Each of these notes of musical instruments would have its own train of harmonic overtones, which would give it definition. Professor Dayton C. Miller has shown [1] that the notes of the clarinet contain the seventh harmonic as an overtone of some intensity; but the note of this instrument

[1] *The Science of Musical Sounds*, p. 201.

is singularly smooth. The periods of this harmonic recur, in groups of seven, in each period of the fundamental, and the two pure tones blend perfectly. Even the eleventh harmonic appears in the note of the clarinet as an overtone of appreciable intensity.

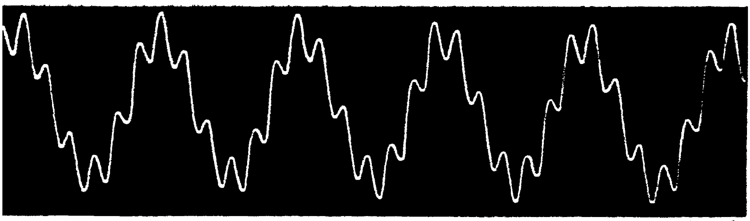
If the sound-curve for the note of the clarinet is drawn, as Professor Miller draws it with his phonodeik, the wavelets corresponding to these harmonic overtones are found to repeat, so many times exactly, in each wave due to the fundamental. The composite wave therefore keeps repeating without change of shape; and this appears clearly from the trace which the phonodeik makes of the note of the clarinet (see Fig. 23, Plate II). This trace may be contrasted with that of a tuning-fork struck vigorously so as to sound an inharmonic overtone (see Fig. 24, Plate II). The wavelets corresponding to the inharmonic overtone do not recur, so many times exactly, in each wave due to the fundamental. The composite wave therefore keeps changing its shape. The inharmonic overtone produces an alteration of shape which, so to speak, creeps along successive waves. The same thing would happen if we tried to build up a musical note by means of overtones whose intervals were those of equal temperament. Such overtones would be inharmonic in varying degree, as is evident from the right-hand part of Fig. 21.

Provided always that we have convinced ourselves that to draw inferences about musical theory, directly, from the harmonic series is to follow a will-o'-the-wisp, there is one arithmetical convenience about the series which we can use as an aid to memory when the succession of notes shown in Fig. 22 has become familiar. We may use Fig. 21, with advantage, to remind ourselves that it is only a convenience. In Fig. 21 all the notes of the harmonic series from that numbered 8 to that numbered 16, except the eleventh, thirteenth, and fourteenth, are opposite a note of some musical interval. We may use them to call to mind the arithmetical ratios between the rates of vibration of notes which form the more important musical intervals when these are tuned ideally. The eighth and ninth notes differ by a major tone: the ratio of a major tone, when tuned with ideal exactness, is 9/8. The twelfth and sixteenth notes, and therefore (dividing by 4) the third and fourth ones, differ by a fourth: the ratio of the fourth is 4/3. The ninth and sixteenth notes



Dayton C. Miller

FIG. 23. Sound-curve of the note of a clarinet, made with the phonodeik



Dayton C. Miller

FIG. 24. Sound-curve of a tuning fork when struck vigorously so as to produce an inharmonic overtone

differ by a minor seventh: the ratio of the minor seventh is 16/9. For the major sixth we go outside the octave. If we move down an octave from the twelfth note we come to the sixth note of the series; and the interval between the sixth note and the tenth is a major sixth, because it is the sum of a fourth and a major third. Consequently the interval between the third and fifth notes is also a major sixth: the ratio of a major sixth is 5/3. All these ratios assume that the intervals are tuned ideally; and they ignore the limitations of the ear, discussed in the first essay in this book. Observe, very carefully, that where colons appear in this paragraph the word 'therefore' has never been inserted. We must *never* make the facile assumption that in the arithmetical ratio lies some derivation of the interval from the notes of the harmonic series. A musical interval is something recognized by the ear and the brain. The effect on our aural perceptions *is* the musical interval. To understand our perception of intervals we must begin with the musical ear, as Helmholtz did.[1] To understand how physical factors in musical sounds help the ear to give definition to the various intervals, a definition which changes in degree from interval to interval, we turn to his theory of dissonance,[2] which is concerned with the sensations of the musical ear.

[1] It is easy to calculate from Fig. 6, p. 22, the ratio of the rates of vibration of concords played perfectly in tune. For example, in the major sixth, the fifth harmonic of one note (which vibrates five times as fast as its own prime) and the third harmonic of the other note (which vibrates three times as fast as its own prime) form a unison, i.e. they vibrate at the same rate. It is simple arithmetic to prove that the rates of vibration of the two primes *must* be in the ratio 5/3, within such limit of accuracy as is demanded by the interval's 'definition' in our ears. Here, then, is the reason for the ratio. It is an inevitable arithmetical coincidence that there must be a corresponding interval between two of the notes of the harmonic series. But while musical intervals depend on the properties of our ears (which make them sensitive to beating), the laws of arithmetic do not.

[2] See p. 23.

VI

THE SOUNDS OF DISTANT MUSIC

Acoustics was long the Cinderella of the physical sciences. DR. G. W. C. KAYE, F.R.S., Presidential Address, Section A, British Association, 1937.

MUSIC has often stimulated inquiry into sound as a branch of physics. Pythagoras had used the monochord to determine the ratios between the lengths of strings which sounded the consonances of the octave and the fifth; but the earliest discussion of sound, as an experimental science, is to be found in the pages of Marin Mersenne's *Harmonie Universelle* (1636), in which the approach was musical. Students now tell us that, in his investigations, Mersenne was anticipated by Galileo; but as Galileo had incurred the displeasure of the Inquisition, his results were not published until two years after the appearance of Mersenne's work. Music finds a place in Galileo's approach to sound, as it did in Mersenne's. In his *Two New Sciences* (1638) he writes: 'I may give you some of my ideas concerning certain problems in music, a splendid subject.'[1] It might therefore be expected that the science of sound should constantly have been presented in aspects which make a direct appeal to the musician. In fact it is seldom so presented.

Reasons for this are not far to seek. As a branch of physics, sound interests the mathematician, who derives the laws of vibrating bodies from the science of dynamics: his is an advanced study, of interest to few musicians. On the other hand, the idea of sound as something transmitted to our ears by the air has been familiar for at least two thousand years: Aristotle had explained this idea in a manner which would earn good marks to-day in a schoolboy's examination paper; and to men who accepted the transmission of sound by air as a perfectly natural idea, the study of light provided much more intriguing problems. Thus, while a bell rung in a vacuum is inaudible, light from the sun travels to us through space in which there is no atmosphere. How does it do this? The answer of science has varied from time to time. Newton advanced a corpuscular theory of light. Thomas Young and Fresnel won recognition for a wave-theory; and to explain

[1] Quoted by Dayton C. Miller, *Anecdotal History of the Science of Sound*, from a translation of Galileo's work by Henry Crew and A. De Salvio (1914).

these waves all space and everything in it was supposed to be filled with an ether. To-day this ether is regarded as merely a 'conception' that is useful on occasion; but the nature of light seems to present as intangible a problem as ever. Early investigators often turned to sound, carried through the air by vibrations, for analogies of wave-motion used in conjecture about light. Perhaps this explains a tendency, evident in the older text-books, to treat sound as if it were light's poor relation.

Now sound and light, despite some features in common, are in many ways quite different. For example, since sound cannot travel through a vacuum, it could not travel at all through interstellar space into which the atmosphere does not extend; but we can see the stars. Again, sound travels much more slowly in air than it does in a light gas like hydrogen; it even travels more slowly, to an appreciable extent, in cold air than in warm air. At first sight this may appear to suggest an analogy with light; for when light passes from air into a dense medium like glass its speed is reduced. But when sound is transmitted in a solid like glass or metal, it travels ten or fifteen times as fast as it does in air. Then again, if we use a polished mirror we can reflect light. But the most perfectly polished mirror appears as an inefficient reflector of light when compared with a smooth solid surface of painted plaster, on a rigid wall, as a reflector of sound. The comparison of a wave-length of sound with a wave-length of light is to be reckoned in millions. Consequently the phenomena of sound take place on a vastly larger scale, as a rule, than those of light. Let us therefore consider what we can learn about sound, not from small-scale laboratory experiments, but from familiar sounds of music heard after it has travelled some distance, as we hear the sound of an orchestra in a concert hall, or the choir in a cathedral, or even distant church bells in the country.

In infancy our knowledge of our surroundings is derived from the indications of our senses, and becomes mainly a matter of inference. We soon learn to use our ears to determine the direction of some sounding object. Because it indicates a novel effect of sound, one of our first surprises, as we grow older, is the echo. We hear sounds reflected from a building in a way that makes us think that the sounding body is in the wrong direction. We recognize that sounds we make ourselves are thrown back to us by a wall or a distant

cliff. Reflection of sound becomes very important in the making of music in music rooms and concert halls, for it causes reverberation, and if this were lacking they would feel oppressively dead to the ears of the artist and the listener. Reverberation is due to the persistence of a confused sea of echoes, a choppy sea, as it were, rather than one swept by an ocean swell. The vibration of the air in a room or hall is maintained by these diffused echoes for a longer time than it would last in a room surrounded, say, by curtains.

What do we mean when we say that sound is transmitted in air by means of vibrations? In the second of these essays the mechanical principles of Professor Dayton C. Miller's phonodeik were described. We then saw that the attraction of this instrument for musicians lies in the fact that its construction and use make the nature of a sound-vibration in air quite evident. They exhibit the sound-vibration as a to-and-fro motion along minute straight lines pointing in the direction in which the sound is travelling. The phonodeik has a kind of mechanical ear-drum, and we may think of the vibration in the air as alternately pressing it in and sucking it out. This idea of variation of pressure in air disturbed by sound is very important. The air is set in vibration because the pressure that is piled up in any place always tries to disperse. The variation of pressure is almost incredibly small; if it were not so it would tend to burst our ear-drums. It is this difference of pressure, between its two extremes in a vibration, which causes the sound to travel onwards as the difference of pressure disperses.

What, then, happens when a sound-wave in air, consisting of alternate slight increases and slight reductions of the pressure of the air, reaches a hard solid surface? A light fluid substance like air is easily moved or compressed, while a hard solid surface, rigidly fixed, resists pressure very easily. For this reason, tiny changes of pressure in air, as found in a sound-vibration, will cause hardly any vibration of the same kind in the solid. For all practical purposes, the sound-wave would be unable to enter the solid; and theory and experiment alike show that the amount that enters is negligible. The only thing left for it to do is to bounce off the solid, as it were. That is why a solid surface is such a good reflector of sound. Whether the sound falls perpendicularly or obliquely on the solid, it will be reflected, very much as a tennis-ball striking a wall bounces off it. We see, therefore,

why a sound in a room with smooth hard walls re-echoes from them till it is diffused all over the room. This is the explanation of reverberation. A reasonable degree of reverberation is necessary in a music room or concert hall, but it must not be excessive. In a concert hall good musical effects are heard if a period not exceeding two seconds elapses before a loud sound fades out completely.

Not all the walls or their coverings, or the contents of a room, are hard solid surfaces. All surfaces, in fact, may be porous to some extent, and curtains, carpets, and the clothes we wear are decidedly so. Sound can enter such porous substances, and, as a form of energy, it is turned into heat in their interstices by effects of a frictional nature. The sound disappears as sound, and we say that it is absorbed. This is important in controlling reverberation, by upholstery or by absorbent plasters on the walls and ceiling. It explains why a concert hall is less reverberant when the audience is present than when it is empty.

Absorption of sound has a related effect on music in large buildings, such as cathedrals, in which reverberation is very marked. Direct measurements which the physicist can make have proved that substances like stone, brick, and wood absorb more of the vibration of high notes than of low ones. Broadly speaking, the higher the note the more it is absorbed every time it strikes the surface of such a substance. Now, sound travels about 1,100 feet in a second, so that in a cathedral in which a chord on the full organ may take 5 seconds or more to fade away completely the sound will have travelled 5,500 feet, which is more than a mile. Obviously, therefore, it will have been reflected repeatedly in that time, and each time it is reflected it loses, by absorption, rather more of its high-pitched ingredients than of its lower ones. This explains the mellowing effect of the building on music heard in it. The higher partial tones to which any harshness of musical tone[1] is due fade more rapidly than the deeper ones. This also explains why the mistuning involved in equal temperament is less objectionable in a cathedral organ than in a chamber organ: for it is the higher partial tones in the notes of the organ, particularly those of the reeds and mixtures, which emphasize the mistuning, as Helmholtz showed.

[1] The word 'tone' is made to do duty in music and acoustics in four or five different meanings: see *Music and Sound*, p. 103 fn., and *Music and Letters*, 1939 (Oct.), 20, 372.

The compressions of air in a sound-wave can hardly penetrate a solid surface at all. But if the solid surface is flexible, instead of being rigid as we have so far supposed, they can, so to speak, bend the surface. That is why a thin partition is not sound-proof. Sound may cause the whole surface of such a partition to vibrate; and sound-waves will then be thrown off by the vibration of the surface on the other side of the partition. (Recall, as something similar, the powerful sound-waves that are thrown into the air by the vibrations in the soundboard of a piano.) The sound need not fall perpendicularly on the surface of the partition to make it vibrate like this. Sound-waves are due to rapid but minute alterations of pressure in the air, and if they reach the partition obliquely, or even travel over its surface, they can press it in or suck it out. For this reason, when a sound reaches a thin partition from any direction, some of it appears to pass through the partition as light travels through a glass window, though what actually happens is something quite different. In short, we may say that all the effects we have been considering are not easy to understand if we confuse our ideas by supposing that sound behaves like light.

We may now consider some other effects, familiar in sounds from a distance; and as we wish to distinguish them from reflection, which always occurs in a closed space, let us go out-of-doors into the open air of the countryside. For the present, let us ignore any sound that reaches the ground or the grass, and is there absorbed, or scattered by reflection.

If the air were all at the same temperature, sound would travel equally in all directions and it would travel at the same speed. We are thinking of some musical sound, and we naturally assume that its source is near the ground. Fixing our attention on a particular compression, we know that it will travel outwards from the source and after a short time it will exist as a compression spread out (so far as vibrations that miss the ground are concerned) all over the surface of a hemisphere. Each moment the hemisphere in which the compression lies becomes bigger and bigger and the energy in it has to spread over a constantly increasing surface. Therefore the sound naturally becomes fainter the farther we are away from its source. The energy of the sound falling on a square yard 100 feet from the source has to be spread over an area twice as high and twice as wide when we are 200 feet away; that is, it is spread over 4 square yards. The

energy, or intensity, of the sound is reduced to one-quarter of what it was when we were 100 feet away from the source.

It must not be thought that the sound 200 feet away is only a quarter as *loud* as the sound 100 feet away. Loudness is perceived through an aural sensation, intensity is a physical measurement. Loudness cannot be *measured* by intensity. As a comparison of loudness of sounds which we should represent as near the top of the treble clef, the physicist would say that when we were 100 feet away from the source the loudness is only 6 phons more than when we are 200 feet away. To explain this he might add that the noise in an express train with the window open is about 60 phons louder than a watch ticking 3 feet from our ears. But all this is another story.[1]

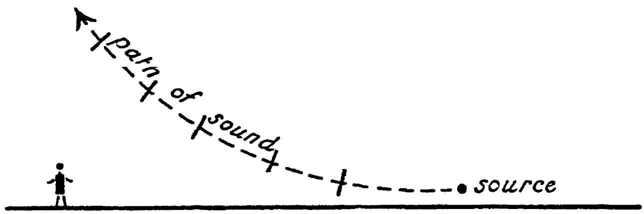
Air is hardly ever found in the condition we have supposed. As we ascend from the ground the temperature changes. Normally, in the day-time, we should expect to find that it became cooler as we ascended. On a hot summer day the ground becomes very warm, and air near the ground becomes heated. Consider what must now happen to the sounds which reach us (or fail to reach us) from a distance. We have pictured a compression, in a sound-wave, as travelling outwards from the source in the shape of an ever-increasing hemisphere. The small amount of it which travels in our direction will be found in a very small area of the hemisphere, which we may regard as a small plane. This small plane we may call the wave-front of the sound that travels to us. Now, when contrasting and comparing sound with light we noted that sound travels faster in warm air than in cold air. When the air nearer the ground is warmer than the air higher up, the sound will travel faster near the ground than it will do higher up. This will tend to tilt the wave-fronts as in *A* of Fig. 25. The dotted line represents the path of sound, and the solid lines drawn across it represent the wave-fronts. The sound will tend to pass over our heads. This explains why sounds from a distance are often unexpectedly faint. The background of noise in the day-time tends to drown distant sounds, but is not enough to explain this effect, which is noticeable in a country place where we may still find a quiet spot.

On a cool summer evening, 'when all the air a solemn

[1] It is told in the author's *Decibels and Phons* (Oxford University Press).

stillness holds', distant sounds reach us with surprising distinctness. We are all familiar with the way in which the sound of distant church bells travels almost incredible distances under such conditions. Why is this? The explanation is that the sound-waves are bent down instead of being bent

A



B

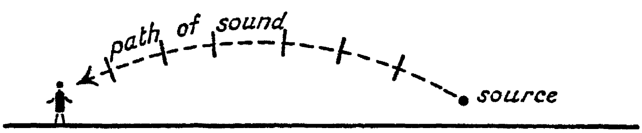


FIG. 25. Diagrams showing, on a very exaggerated scale, refraction of sound in air as an effect of differences of temperature at different levels

up. On a cool, still summer evening, when dew is falling, the air near the ground is colder than it is higher up. We know how the cold air may then roll down into hollows where a mist may collect; or if we ride down-hill on a bicycle we find it much colder at the bottom of the hill. Up above, the air is warmer. This reverses the state of the atmosphere we usually find in the day-time. Sound travels faster in the warm air. The wave-fronts are tilted as in *B* of Fig. 25. Much more sound reaches our ears from the distant source.

Another instance may be cited. Readers who remember 'In Summer Time on Bredon', possibly from one of its settings as a song, will recall how of a summer morning 'the bells they sound so clear . . .' to the listeners on Bredon Hill. The air in the valleys may still be colder then than that on the hill-sides, as it was in the night. (Plants are more likely to be nipped by a night frost at the bottom of

the valley than on higher ground. When the valley air is still cold, sound ascending from the valley will be bent towards the hill-sides and some of it may be pictured as creeping up them to the listeners. Early on a bright sunny morning the church bells will sound clearer on the hill-sides than they do in the afternoon when it is hot and close in the valley. We have been discovering large-scale experiments to demonstrate, much more convincingly to musicians than by a small-scale experiment in the laboratory, the effect of the bending of sound-waves or *refraction*.

It might be supposed that, just as the speed of sound is affected by alteration of the temperature of the air, so it will be affected by the reduction of barometric pressure as we ascend to a higher altitude. This, however, is not so. Changes of barometric pressure do not affect the speed with which sound travels in air.

In a wind, something like the effect shown in Fig. 25 also occurs—if we suppose the wind to blow from left to right in *A*, and from right to left in *B*. The wind travels more slowly near the ground than it does higher up. It will tend to tilt the wave-front of sound from a distance, upwards in a sound travelling against the wind as in *A*, and downwards in a sound travelling with the wind as in *B*. As a wind travelling 60 miles an hour only travels 88 feet per second, and as sound travels about 1,100 feet per second in air, even a hurricane could not blow the sound away. Its most important effect is to bend the sound's path up or down.

It is interesting to calculate the effect of wind under conditions in which it would not bend the sound's path in this way. If the listener were suspended a considerable height above the ground in a steady wind, he might find himself in a region in which the air was moving uniformly above and below him. Suppose he were then listening to a whistle, at the same level, sounding a note just above the treble clef. Suppose everything to be calm at first and that the wind then began to blow steadily from him to the whistle with speeds that increased by successive small steps. Suppose further that, by some means, it could slip past his body quite silently and without making any eddies to disturb its steady motion. To reach his ears, the sound from the whistle would have to travel farther when the wind was blowing than when all was still. We might expect this to reduce its loudness. But it would be necessary for the wind to blow

nearly eighty miles an hour before the loudness of the whistle, as heard by his ears, would be reduced by one phon; that is to say, it would have to rise to more than gale force before it made any perceptible reduction of loudness—a rather surprising result to those of us who think of the wind as blowing the sound away.

The spreading of a sound-wave round and behind an obstacle in its path is interesting and important. Here again analogy with light does not help the beginner. The shadows thrown in sunshine, or in any direct illumination from a point source, are very sharp. Spreading of light round an object can easily be demonstrated by using something too minute to throw a normal shadow, and the problem is to find such an object. When we turn to sound, however, the position is reversed; the problem is to find something big enough to throw a complete sound-shadow. We know, however, that if we stand close to a large building it may completely screen a sound from our ears. Big Ben is not audible if we cross the Horse Guards Parade and stand close to the large block of government buildings which then hide the Westminster Clock Tower from us. The buildings are throwing a complete sound-shadow over us. But more widely familiar is the way we hear sounds, though much reduced in volume, round corners. The bells of a cathedral surrounded by small houses are audible in the streets because their sound seems to steal over the roofs and pour down on us. What really happens is that the sound-wave, after passing an obstacle, tends to spread out into the air behind it; but the sound-wave will not make so much disturbance there as it would do if it travelled there directly; consequently the sound will be fainter.

Finally, there is one effect in sounds heard in the country from a distance which is specially interesting to musicians who know that the characteristic quality of particular instruments, or particular organ stops, depends on the number and intensity of the overtones in their notes. If we stand close to a church tower with an untuned ring of bells in it, we are conscious of a jangle of tones in the sound of each bell. If we hear the same bells a mile or two away, say when rung for evensong, we find them much sweeter. The sound of a bell has almost a round, flute-like quality then. Why is this? The effect is comparable to the mellowing effect of reverberation in a cathedral on the tones

of the organ; but the cause is not quite the same. Think of a post driven into the bed of a river near the bank. If a rapidly moving launch passes along the river it throws big waves from its bow and stern, followed by smaller ones. Between successive waves there will be a space of some feet. In other words, they will have a considerable wave-length. When these waves reach the post they just roll past it, and reach the river bank as if the post were not there. Now suppose that when the river is calm we go to the post and make little ripples in the water near it with our hands. They would have a short wave-length. These ripples would not pass a post of any size. Behind the post the water will be hardly disturbed. The ripples which hit the post would be reflected there and scattered.

Something like this happens to sound travelling over the countryside. Some of the sound would find its way through the trees and hedges. The sounds with long wave-lengths, that is, the deeper sounds, would do so best. The sounds with short wave-lengths, that is, all the high-pitched ingredients in a sound, would tend to be scattered, as the ripples were scattered by the post in the river. Now here we have, at last, an analogy with light which we may use with advantage. The setting sun looks red. That is because its rays have to travel a long way through air in some of which there is a certain amount of dust, and perhaps smoke. The fine particles of the dust and smoke (for smoke consists of tiny particles of carbon or tarry matter) scatter the light of short wave-length more than that with longer wave-length. Theory tells us that even the molecules of gases which make up the atmosphere can do this. Now, blue light has a wave-length about half as long as that of red light. The rays of the setting sun travel through much more of the earth's atmosphere than the sun's rays at mid-day; and much of this atmosphere is dust-laden. The effect is to filter out of the rays more of the blue light than of the red light. Consequently red is the predominant colour in the light that gets through.

In exactly the same way the high-pitched overtones of the church bell, which cause the jangle, are filtered out to a large extent by the trees and hedges, with their branches and foliage, through which the sounds pass. The high-pitched sounds may also be absorbed a good deal more than the lower ones by different types of ground over which they pass,

and this effect becomes more important when the sound is always tending to be bent down to the ground. The very air itself can filter out high-pitched sounds in the same way, to an extent that depends on its humidity.[1] Ohm's law of acoustics tells us that the quality of the sound heard will be altered when the higher-pitched tones are partially filtered out of it. It will become sweeter. 'Heard melodies are sweet, but those unheard are sweeter', sang the poet. Matter-of-fact science comes along and tells us that while heard melodies are sweet, those which reach us from a considerable distance in the country are sweeter; and to explain this fact it explains to us the properties of the musical ear.

[1] Vern O. Knudsen, *J. Acoust. Soc. Amer.*, 1931, **3**, 126.

VII

THE SCALE AND THE MUSICAL EAR

Truth comes more easily out of error than out of confusion. Author unknown.

Of course Wagner thought only in equal temperament. ALEXANDER J. ELLIS [1]

Wagner . . . whose every work proves the writer to have had the pure scale inbred in him. C. V. STANFORD [2]

A CLASH of opinion like that of the second and third of these quotations requires no careful distinction between the composer and the 'theoretician'. The distinction is insistent; and no musician will suppose that the 'theoretician' was right. But he may be surprised to learn that academic musical theory had produced such a 'miasma',[3] fifty years ago, that Stanford's meaning was not always understood. What is the pure scale? Let us turn to a composer whose musical imagination was certainly unhampered by the intonation of keyboard instruments, and who was content to write music 'To the greater glory of God' which he expected would be sung *in tune*.

Fig. 26 shows the closing strain of the Mass *Corona Spinea* by Taverner, written in the first quarter of the sixteenth century to be sung by unaccompanied voices in six parts: treble, alto, two tenors, and two basses. It is transcribed in close score to assist readers unpractised in reading open score

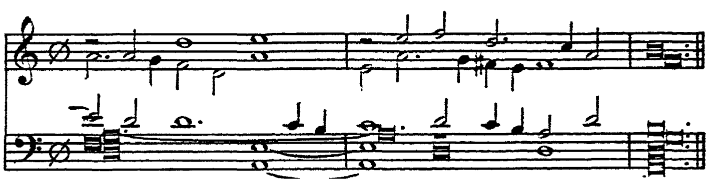


FIG. 26

on six staves. The haunting beauty of this strain will command the attention of any one unacquainted with the early treasures of our English musical heritage. The music, being of its period, is modal: its intonation is anchored to the long-sustained A of the second tenor, which unquestionably will tend to move down by a major tone to its 'final' on G. Now consider what must happen to the intonation of the D, G,

[1] From a translator's footnote to the second English edition of *Sensations of Tone*, p. 339.

[2] *Musical Composition*, C. V. Stanford, p. 18. [3] Ibid., p. 10.

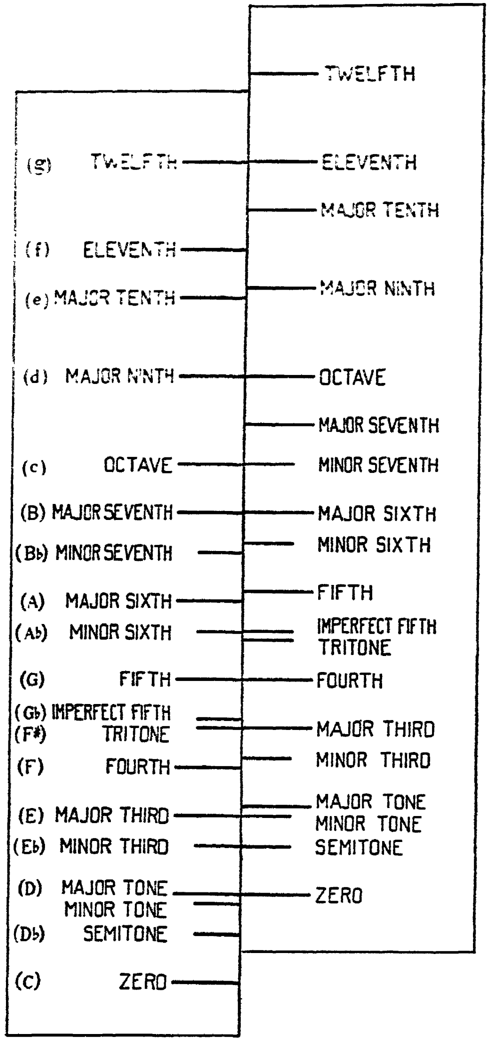

TWELFTH
(g) TWELFTH
ELEVENTH
MAJOR TENTH
(f) ELEVENTH
(e) MAJOR TENTH
MAJOR NINTH
(d) MAJOR NINTH
OCTAVE
MAJOR SEVENTH
(c) OCTAVE
MINOR SEVENTH
(B) MAJOR SEVENTH
MAJOR SIXTH
(B♭) MINOR SEVENTH
MINOR SIXTH
(A) MAJOR SIXTH
FIFTH
(A♭) MINOR SIXTH
IMPERFECT FIFTH
TRITONE
(G) FIFTH
FOURTH
(G♭) IMPERFECT FIFTH
(F♯) TRITONE
MAJOR THIRD
(F) FOURTH
MINOR THIRD
(E) MAJOR THIRD
MAJOR TONE
MINOR TONE
(E♭) MINOR THIRD
SEMITONE
(D) MAJOR TONE
MINOR TONE
ZERO
(D♭) SEMITONE
(C) ZERO

FIG. 27

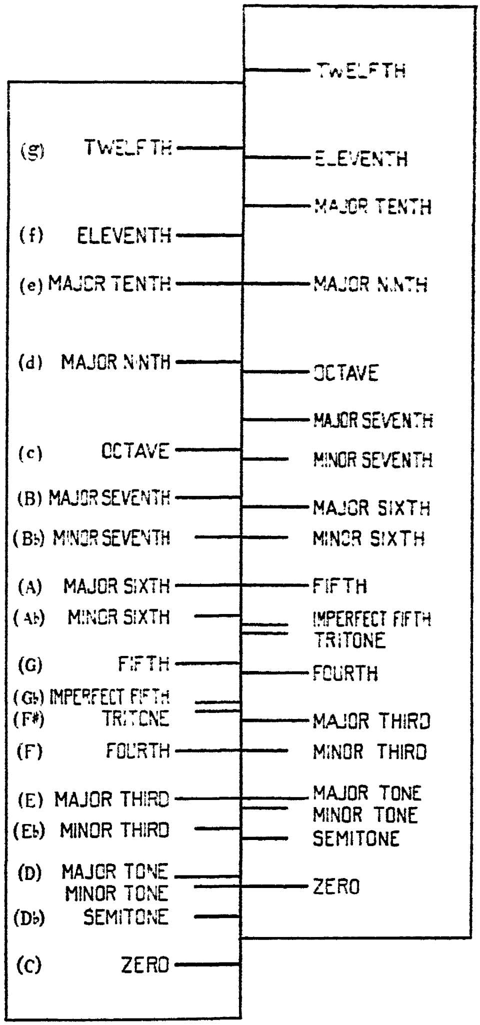

TWELFTH
(g) TWELFTH
ELEVENTH
MAJOR TENTH
(f) ELEVENTH
(e) MAJOR TENTH
MAJOR NINTH
(d) MAJOR NINTH
OCTAVE
MAJOR SEVENTH
(c) OCTAVE
MINOR SEVENTH
(B) MAJOR SEVENTH
MAJOR SIXTH
(B♭) MINOR SEVENTH
MINOR SIXTH
(A) MAJOR SIXTH
FIFTH
(A♭) MINOR SIXTH
IMPERFECT FIFTH
TRITONE
(G) FIFTH
FOURTH
(G♭) IMPERFECT FIFTH
(F♯) TRITONE
MAJOR THIRD
(F) FOURTH
MINOR THIRD
(E) MAJOR THIRD
MAJOR TONE
MINOR TONE
(E♭) MINOR THIRD
SEMITONE
(D) MAJOR TONE
MINOR TONE
ZERO
(D♭) SEMITONE
(C) ZERO

Fig. 28

and C in relation to this A, or alternatively to the intonation of E, F♯, and A in relation to the initial D of the second bass, if the music is sung perfectly in tune. As explained below, the result is an acoustical paradox to the 'theoretician' whose 'scale' consists of notes rigidly fixed. Something must give way; and it will either be his scale or the intonation of the singers. The dilemma exists only in the imagination of the 'theoretician'. The ultimate criterion is beauty, and the final judge is the musical ear.

The trained ear of the musician is extremely sensitive to a mistuned interval in a concord, unless it lasts only for a moment. It is relatively insensitive to slight adjustments of intonation which are required by some new concord. Witness also the licence which the ear allows the violin player in the intonation of notes which are not an essential part of the prevailing harmony. The violin player is not concerned to play F♯, *as a decorating note*, in its theoretical place below G♭. We have therefore to think of the pure scale as a *scale system* in which the essential intervals are in tune and the intonation is flexible.

It is easy to realize that intonation must be flexible if essential intervals are to be in tune. This is perhaps most easily seen from a diagram of the scale in which all the musical intervals are drawn in their correct proportions with theoretical exactness. In such a diagram all the intervals will be measured from the same zero, just as inches on a foot-rule are all measured from the same zero. Two such diagrams, the one left-handed and the other right-handed, as it were, may be fitted together and used as a musical slide-rule. They are so shown in Figs. 27 and 28. The construction and use of a musical slide-rule like this has been fully described by the author elsewhere,[1] and the description need not be repeated here. In the left-hand half of either figure certain intervals are shown with longer graduations, and opposite them the notes of the major diatonic scale of C are shown in brackets. These graduations give, with theoretical exactness, the intervals of this scale required for a full close and a plagal cadence. It is easy to check this, with a pair of dividers or a pencil and a slip of paper, by measuring and comparing major thirds and fifths from the tonic, C, the dominant, G, and the subdominant, F. But not all the intervals shown by these longer graduations will serve for

[1] In *A Musical Slide-Rule* (Oxford University Press).

harmony on the second-degree note of the scale, or supertonic, as it is called. In Fig. 28 the right-hand half of the slide-rule is adjusted to show a minor triad on the supertonic of the left-hand half, making the interval D to F a minor third and the interval D to A a perfect fifth. It is evident that, if the triad is exactly in tune, D must move down till it is only a minor tone above C. It becomes a *mutable note*.

This adjustment of the musical slide-rule will make it easy to understand the intonation of the quotation from Taverner. It illustrates modification in the intonation of D, G, and c, in relation to the long-sustained A of the second tenor, which was indicated above. Alternatively we may think of modification in the intonation of E, F♮, and A, in relation to the initial D of the second bass, by looking at the musical slide-rule as adjusted in Fig. 27. In Fig. 28, A on the left-hand half is opposite the fifth on the right-hand half; but notes for D, G, and c on the left-hand half are also wanted opposite the zero and the graduations for the fourth and minor seventh on the right-hand half. In Fig. 27, D on the left-hand half is opposite the zero on the right-hand half; but notes for E, F♮, and A on the left-hand half are also wanted opposite the major tone,[1] the minor third, and the fifth on the right-hand half. It is evident that some notes on the left-hand half in either figure must move. We may observe that Fig. 27 also exhibits the intonation of a perfectly tuned chromatic seventh on the supertonic, D, F♯, A, and c; and makes it evident that in this chord we must be prepared to move A.

In these illustrations of the flexible scale system, whether that of the sixteenth century or that of modern times, we have assumed theoretical exactness of intonation. To suppose that the artist can produce, consistently, an intonation with equal exactness is to ignore the natural limitations of the human ear as an instrument for estimating intervals that sound in tune. We must constantly bear this in mind, and not confuse it with faulty intonation which does not sound in tune.

We deceive ourselves when we think of the musical scale as consisting of *notes* like the notes of a keyboard instrument. The idea of notes comes to mind when we want to record the intonation of a musical composition by means of written marks on the stave. It is confirmed when we construct

[1] Because a perfect fourth is less than a perfect fifth by a *major* tone.

keyboard instruments, which can never play consistently in *theoretically* perfect tune unless they have so many digitals to the octave as to be unplayable. In music, notes have no existence independently of intervals, harmonic or melodic; and the musical scale consists essentially of intervals, as every student of counterpoint learns from his use of concords. Whether or no a particular interval is appropriate to the musical occasion only the ear of the musician can determine.

That music should be sung or played in tune to the complete satisfaction of the trained ear all musicians will agree. To play perfectly in tune is, or should be, the constant endeavour of a quartet of string players; and we know the silken beauty of tone produced when they succeed. They then approximate to the pure scale within those varying limits, minute though they may be, which are all that the trained ear asks for in the varying conditions of musical performance.

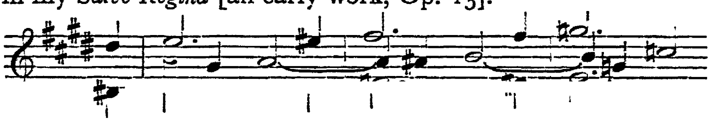
The academic theorist who, clinging to the idea of a fixed intonation, solved his acoustical problems by his belief that music of the classical period was written in equal temperament, started with fallacious premisses, musical and scientific. Scientific premisses that were fallacious: because when he proceeded to prove, from the arithmetical ratios of the vibrations in the air, that music played or sung in just intonation must inevitably lose pitch in a succession of commas, he omitted the ear from his calculations altogether. The only *practical* meaning of just intonation is playing or singing 'in tune', and we have learnt of the part played by the ear. Musical premisses that were fallacious: because unskilled technique in writing music to be sung unaccompanied may cause loss of pitch which a more experienced composer would avoid. The theorist cannot judge of this from the score unless he has studied composition. Stanford recorded that he had 'more than once heard a performance at the same concert of a modal madrigal and a complex modern part-song, where the former ended exactly on the pitch and the part-song nearly a tone below it. The fault was with the composer of the part-song, not with the singers.'[1]

The 'theoretician's' faith in equal temperament as a musical solvent has often misled others. It has no basis in reality. Unaccompanied voices encounter an unfair task when they attempt to sing the production of some uninstructed writer

[1] *Musical Composition*, p. 148.

with a keyboard mind, who has sprinkled his score with chromatics under the impression that there is no difference between F♯ and G♭, and that all semitones, chromatic or diatonic, are equal. The result is almost sure to be an uncertain intonation and an uncomfortable loss of pitch. The judicious use of occasional chromatics may present no great difficulty to a good choir, but the musician has much to learn before he can write gratefully for voices. Even the scholarly Hauptmann (1792–1868), on occasion, set his choir a task which at the time of writing he failed to realize was beyond them. A piece of self-criticism, to be found in a letter[1] which he wrote in 1843 to Spohr (who made free use of chromatics), shortly after he became Cantor of the *Thomas-schule* in Leipzig, is pertinent to any discussion of the musical scale:

'I hope we shall soon venture on your Psalms; I was afraid to begin with them. The Chorus [of the *Thomas-schule*] is firm as a rock in diatonics, with figures and *colorature ad libitum*, but in chromatic music, they are no better than their fellows. To sing chromatic passages in tune, presupposes a real education in music; something more than hitting the note is required; the singer must feel for himself the harmonic progressions. This I learn, to my mortification, every time that I hear this passage in my *Salve Regina* [an early work, Op. 13]:



Mechanically, there seems to be nothing amiss, but when it comes to the performance, I am always in Purgatory. The sharpness does not lie in the vocal intonation. . . . There is no justification for a composer who makes a pianoforte accompaniment indispensable for the performance of choral music; and the old masters were far from wrong, in adhering to a very peremptory code of laws, to regulate such compositions as this. I am more ashamed of such a passage, than I should be of palpable octaves and fifths, which anyhow are no hindrance to pure intonation.'

The passage is most revealing when it is remembered that Hauptmann was a violin-player and had the clearest possible conception of the nature of the musical scale. His criticism of the piano, as an instrument to accompany the violin, was not of its *faulty* intonation, due to the mistuning implied in equal temperament, but of its *rigid* intonation. He continued:

[1] *The Letters of a Leipzig Cantor* (Eng. trans.), vol. ii, p. 200.

'Had I no natural consciousness of the pure tone, how could I recognise the sharpening of it as the leading-note—its flattening as the minor ninth.'[1] Spohr's notion that singers should be taught intonation from the equal temperament of the piano excited his mingled indignation and amusement; and equally he set right those 'theoreticians' who imagined the musical scale as demanding that each note of music should be played in theoretically just intonation (see p. 1). To put ourselves in Hauptmann's place we must remember that Johann Sebastian Bach's music was being rediscovered in his day, while his collection of Palestrina's music was mostly in the form of manuscript copies in his own hand.

If, then, the musical scale is a flexible thing, and if the musical ear wants to hear essential intervals played in tune, how is it possible to use a keyboard instrument with its fixed intonation, and why is the mistuning, called equal temperament, tolerable on the piano? Here is a problem for which the man of science has not yet provided us with a complete answer; partly, it may be, because, as musicians, we do not make clear to him the nature of the scale system which the piano does its best to suggest. It happens that the string of a percussion instrument like the piano, struck by an elastic hammer in the right place, does not assert the definition of its note, and therefore its intonation, as the sustained note of a violin does. Helmholtz was the first to explain why this is so; and for his explanation the reader may turn to his *Sensations of Tone* or to books on musical acoustics.[2] The result is that, when the piano is used as a solo instrument, the musical ear and brain have opportunities of perceiving an intonation slightly different from that which corresponds to the vibrations produced by the instrument: are we justified in assuming that, in the conditions of musical performance, they can never take advantage of these opportunities? In the first place, as Helmholtz explained, when the music is moving rapidly we may be certain that the ear has little or no means of detecting the very slight mistuning of musical intervals, on the piano, which is involved in the use of equal temperament. But is this all? What intonation

[1] *The Letters of a Leipzig Cantor* (Eng. trans.), vol. i, p. 150.

[2] The intonation of the keyed instruments of the orchestra, which are tuned in equal temperament, as well as that of the organ and the piano, is discussed in the author's *Music and Sound*, Chap. V, in the light of Helmholtz's theory of dissonance.

does the musician perceive at other times? Modern knowledge of perceptual effects, in general, may well make us hesitate to take it for granted that the musician's aural perception of the intonation of the piano always corresponds, exactly, at these other times to the rates of its physical vibrations.[1] The object of an enharmonic modulation is frustrated unless the musical ear apprehends the enharmonic change. Sir Donald Tovey states that the ear of the musician imagines an enharmonic change on the piano when the unexpected resolution appears[2]; though, as his ear 'hears' the change, he perceives rather than imagines it. Observe that we must not generalize, too hastily, about our aural perception from this statement. The notes of the piano rapidly diminish in intensity, more rapidly indeed than they do in loudness, which is a perceptual effect. As the note ceases to sound, things may well happen to our perceptions which our ears would not permit when the note was first struck.

Such scientific knowledge as we possess, of a precise character, about piano tones is limited to single notes. Diagrams of the sound-waves, produced in the air, have been drawn by the phonodeik[3] and other forms of oscillograph. They are very unlike the sound-curves corresponding to steady tones, such as those of organ pipes shown in Plate I. For perhaps the first ten vibrations the to-and-fro motion of the air rapidly increases; it then diminishes, though with less rapidity, for perhaps another twenty or thirty vibrations. After that there is a steady but much smaller contraction of the motion. Moreover, successive vibrations in the sound-curve are not identical in form. The changes indicate changing intensities in the various overtones. The rates of vibration of the more frequently used notes of the piano range from, say, 100 to 1,000 per second, and it is quite impossible for the ear to make perceptible pictures, in the brain, of each vibration. Our mental image must always present the result of a kind of blend of a number of

[1] A theory that vibrations are 'telephoned' to the brain as frequencies, by the ear, commands much less support than the opposing 'resonance theory' which we owe to Helmholtz (see *Music and Sound*, p. 49). For example, it appears to be inconsistent with observations about pitch referred to on p. 48. A concise technical account of modern scientific opinion will be found in *Theories of Sensation*, E. F. Rawdon-Smith (1938).

[2] *Encyclopædia Britannica*, 14th ed., article on 'Harmony'.

[3] See *The Science of Musical Sounds*, D. C. Miller, p. 209.

vibrations that have just happened. How then is our perception of the tone related to the vibration in the air?

These investigations of piano tones are concerned only with single notes, long sustained; and they do not take us very far. In Schumann's *Carnaval*, for Pianoforte, Opus 9, there are three short pieces, called 'Sphinxes', which consist of long-sustained single notes. But what musicians wish to know is: What happens to our perception of the intonation of all the other music written for the piano? What is the effect, if any, of the musical context on the aural perception of the musician? Many musicians do not quarrel with the intonation of the piano, as a solo instrument, when the musical context lies in the music itself. But they become conscious of a difference between the intonation of the piano and that of the orchestra in a concerto, when the musical context implies a physical contrast of intonations. Helmholtz was greatly interested in problems of intonation. He wrote, 'When I go from my justly-intoned harmonium to a grand pianoforte, every note of the latter sounds false and disturbing.'[1] Why does the aural perception of the pianist accept the intonation of his instrument as satisfactory? Is it because his ear is lax, not to say lazy, until its complacency is disturbed by physical contrasts of intonation? Or are his perceptions influenced by the training of his ear in the intervals used by the art of music? Most pianists would welcome an explanation which did not reflect on the sensitiveness of their ears, or the intentness of their listening. Is such an explanation to be found?

Many of us whose ears accept equal temperament on the piano are conscious of something not quite satisfactory about the intonation of the organ (whose notes are *sustained*), unless it is played in, say, a cathedral where the acoustical qualities of the building help our ears by filtering out, or cloaking in a sea of sound, the dissonant higher partial tones of tempered intervals, particularly thirds and sixths. The ear of the trained violinist, however, is less complacent. Lionel Tertis is enunciating a fact of great importance in musical acoustics when he insists that: 'The certain road to never-failing perfect intonation in string playing is listening of the most concentrated kind.'[2] This pronouncement is the more significant

[1] *Sensations of Tone*, Eng. trans. of 1875, p. 503.
[2] *Beauty of Tone in String Playing*, Lionel Tertis.

because it is concerned, not with theories of harmony or the scale of the 'New Music', but with beauty of tone. Here we encounter an example of a perception which depends on the degree to which we *attend* to the sensations in our ears. The acuteness of the hearing of any individual, or rather the lack of it, limits his power of detecting differences of intonation; and there are marked differences in natural powers of this kind between different individuals. In turn, the extent to which any individual exercises whatever powers he may possess will often be a matter of musical education and training.

Some have supposed that the ear of the pianist adopts equal temperament as its musical scale. Were that the whole story, his ear would object to the intonation of a good string quartet just as, conversely, the skilled violin-player finds something unsatisfactory about the equal temperament of the chamber organ. But, in reality, the ear of the pianist finds the intonation of a good string quartet particularly beautiful, though he may not know the reason. When we know all there is to learn about listening, these observed facts will fall into an orderly relationship.

The suggestion which emerges from the train of thought followed in the preceding paragraphs is this: that the educated ear of the pianist accepts the intonation of his instrument as something which it does not distinguish from the pure scale; and that this is a perceptual effect. Once the function of the brain in hearing is recognized, the suggestion is a natural one. It invites careful scientific investigation; but it cannot be dismissed as fanciful. There are three factors in musical acoustics which need to be considered: the to-and-fro vibration in the air; the sensory effect on the ear; and the mental picture, the perception of the sound, made by the brain. The vibration in the air is of no significance for the musician, save in so far as it affects the sensations of his ear. The sensory effects on his ear present problems in physiology which have been studied by Helmholtz and his successors; and modern knowledge has made great advances here. But study of the phenomena of aural perception still lags behind. The study of visual perception has made more progress; and Dr. Thouless has drawn the author's attention to an analogy which may help the reader to understand the significance of our suggestion, and may convince him of its inherent reasonableness. It was indicated in a paper written

some years ago by Friedrich Sander.[1] It may be expressed in Dr. Thouless's own words:

'If a square picture is hung vertically as in *A*, Fig. 29, it looks "right". If there is a *slight* angular displacement it is seen exactly as if it were in the position *A*, and still looks right. The amount of displacement that can be tolerated depends on various factors, such as the nearness of other vertical objects, and on individual differences in the perceiver. With a larger displacement we get the effect *B*, Fig. 29, and the picture is seen as "crooked", i.e. it is seen as trying to be vertical but not succeeding, and this is an unpleasant perception. With still further displacement as at *C*, it may no longer look crooked but as in a new position which is just as "right" as *A*. I have no doubt that training in picture

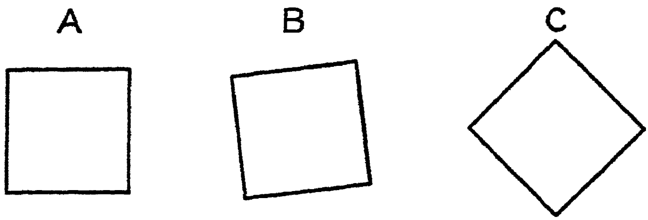


FIG. 29

hanging could make one more easily see small displacements as crooked, but there is no special aesthetic superiority in the person who does. It simply means that more things will look crooked to him. In the same way, I think the special interests of Helmholtz and his training on his harmonium made him sensitive to small deviations from the true scale. I don't think there is any aesthetic superiority in such sensitiveness unless it is required for practical purposes as for playing a violin.'

Many readers will recall one individual of their acquaintance who is fidgety if he sees pictures crooked which most of us are content to regard as straight. He sees, as more like *B*, a very slight displacement of the picture which the rest of us see as like *A*. The aural perception of the pianist, listening to his instrument, we may liken to the visual perception of 'the rest of us', looking at a picture with a very slight displacement which we do not notice. The sensitive ear of the violinist, trained to listen intently for delicate shades of intonation, produces an aural perception which we may liken to the visual perception of the individual who

[1] *Psychologies of 1930* (Clark University Press), p. 196.

sees pictures as crooked if they are so in the least degree. 'The rest of us' do not perceive the faulty intonation of the piano. The good violinist of whom we are thinking is conscious of it.

To understand musical acoustics we must begin with the study of music and get our musical premisses right. As van Dieren remarks: 'The science of the musical research worker has a Looking-Glass complexion. Romantic musings and fabulous mathematics inspire it in turn.'[1] The more confused the problem the more important it is for the musician to simplify the issue for scientific investigation. That is precisely why we may seek to clarify our ideas by first correcting the errors of 'theoreticians'. Nowhere is the application of the dictum that heads this essay more aptly illustrated than in musical acoustics. Regarded with the eye of counterpoint, the issue simplifies itself. It is: How does the musical ear tell whether two notes are in tune? It is because the answer he provides is free from romantic musings and informed by unimpeachable mathematics, that Helmholtz's contribution to musical theory is so invaluable. He proved beyond all doubt that what matters most in musical acoustics is the musical ear, to which we must surely add: and aural perception.

[1] *Down among the Dead Men*, p. 211.

Appendix

AUTHOR'S NOTE

In these essays the relations between acoustics and music have been approached, in the main, from the musical end. This appears to the author to be the natural approach for the musician with little knowledge of science. That it permits of a logical development of the subject he endeavoured to show in *Music and Sound.*

The approach presented the author with one difficulty, the discussion of which is instructive and may interest some readers. Our knowledge of our surroundings is obtained through our senses. Impressions on our senses enable us to make mental pictures of the objects or occurrences which produce them. We infer an identity between our mental picture and the perceived object or occurrence. If our visual perception of an object has the form of a cube we infer that we are looking at a cube. If our aural perception of a vibration in the air has the form of a musical tone, we infer that we are listening to a musical tone. But are we? In other words, by 'musical tone' do we mean something outside our ears that we are listening to, or the mental image we form of it?

Visual perception will help us to understand this question. To begin with, what are popularly called optical 'illusions' are examples of a mental picture which obviously differs from the perceived object. They strike us as so unusual as to merit a special name. But in fact they are examples of quite normal procedure in vision. Dr. Thouless, in his address mentioned on p. 24, states that 'exact correspondence between the details of the retinal image and of what is perceived is the exception rather than the rule.' This observation is concerned primarily with shapes, and with the apparent sizes of objects at different distances; and the discrepancy between the retinal image and what is perceived varies from individual to individual.

Some will say: 'But surely the ear is not like that?' We will recall two aural 'illusions' later; but first consider the phrase: 'The note sounded by the violin'. We know that the quality of a musical tone (the mental picture) depends on the relative loudnesses of the partial tones which are excited in the sensory apparatus of the ear by the complex

vibration in the air. Now the ears of children are, normally, much more sensitive to vibrations of very high frequency than are the ears of old people. Vibrations at a rate between 5,000 and 20,000 per second produce, in the child, an aural perception of a musical tone. In the old person they often produce no impression at all, especially if they have no great intensity. They are then silence to him. 'The note sounded by the violin' contains many pendular vibrations corresponding to a long series of 'overtones'. In the child, with ears that are sensitive to high frequencies, vibrations corresponding to the higher 'overtones' of the upper 'notes' of the violin produce a sensory effect. In the old person they may produce no effect at all. They are not then heard. Both the child and the old person, listening to 'the note sounded by the violin', corresponding to a fundamental and a long series of overtones, will perceive what we call a musical tone; but the child will perceive a tone which is presumably brighter in quality than that perceived by the old person.

Some may object: 'But after all that is a negligible distinction.' Let us then take more extreme instances, to establish the distinction as valid. Nowadays a dog-whistle can be bought which produces vibrations of such high frequency as to be inaudible to human ears; but the dog shows a ready response to them. Some musical instrument might be constructed to emit a complex vibration which could be analysed, mathematically, into a number of pendular or simple harmonic vibrations, certain of which would be of too high a frequency to excite corresponding partial tones in the sensory apparatus of the human ear. But they might easily excite corresponding partial tones in the dog's ear; and the dog would then hear a tone of a shrill quality that could not be perceived by any human ear in these sounds of the instrument. At the other extreme are the cold-blooded animals with rudimentary ears incapable of the aural response of human ears. If their ears are lacking in any sort of cochlea, the animal has probably no sense of hearing of the kind we possess. The alligator, however, has a rudimentary cochlea, and its aural response is more definite. We can hardly expect to obtain first-hand information about the perception of musical sounds by the alligator; but we must assume that it is more active and discriminating than that of cold-blooded animals with simpler ears. It is possible, by electrical apparatus, to observe impulses which travel along

the nerves from the ear to the brain when the ear is excited by vibrations in the air that fall on the ear-drum. Observations of this kind have shown that messages sent by nerve-currents from the alligator's ear to its brain, though vigorous when the nerve is warm, are feebler when it is chilled. The animal's hearing must then be poor. For an analogy, think of other senses. The dog's vision appears to be less serviceable than ours; but we are much less conscious than the dog of the world of smells in which he lives. So also the cold-blooded animal, even if it has a rudimentary cochlea, is presumably less conscious than we are of the details of the world of sound in which we live, and certainly so when its hearing is dulled by cold.

One more example might be added, this time from the human ear itself. A pendular vibration, or simple harmonic motion, in the air normally corresponds to a pure tone as perceived by the ear. But if the pendular vibration is given a greatly increased amplitude, without altering its character, the tone heard by the ear ceases to be a pure tone. The ear itself adds upper partial tones, because of its unsymmetrical construction, and the tone heard is not only louder but altered in character.

Reflecting on these observations and on what we have learnt in these essays of 'illusions' about pitch[1] and about the strike-note of bells, we realize the truth of the quotation from Helmholtz's writings on p. vi. The nature of a musical tone (the mental picture) depends primarily on the peculiar characteristics of the nervous mechanism of the listening ear. The nature of the complex vibration in the air, which is perceived as a musical tone, is, in a sense, a secondary consideration.

The reader who apprehends the truth contained in the last sentence of the preceding paragraph holds the key to the relations between music and acoustics. We must never think of a musical tone as being identical with the physical vibration, in the air, which produces it inside the head of the listener. If the vibration falls on a solid wall of painted plaster, practically the whole of it is reflected, and partially scattered, while remaining a longitudinal vibration in the air. If it falls on a deep layer of porous material, such as cotton wool, practically the whole of it is absorbed, and turned into heat, which is a different kind of vibration. If

[1] See p. 48.

it falls on the diaphragm of a phonodeik it causes the spot of light to vibrate and draw a sound-curve on the photographic film. If it falls on the ear-drum it sets up sympathetic vibrations in the sensory apparatus of the ear which are perceived as a musical tone. The vibration, the heat, the sound-curve, and the musical tone are all completely different things. The correlation between the vibration and the sound-curve depends on the response of the phonodeik. The correlation between the vibration and the musical tone depends on the peculiar characteristics of the nervous mechanism of the ear. These distinctions compel us to attach narrow and precise meanings to some familiar terms, and this is where the author's difficulty arose.

In a scientific treatise, new scientific conceptions can be expounded, and terms to express them can then be defined. Modern research into atomic physics has produced entirely novel conceptions of the structure of matter. To express these conceptions new words have been coined: electron, neutron, proton. But the conceptions came first. In acoustics some new terms, such as 'partial tones', have been coined in the last hundred years. But we still lack a convenient term to denote 'the periodic vibration in air which we perceive as a musical tone', the 'real' thing outside our ears that we listen to, as distinguished from the 'tone' we hear, which is a 'phenomenon' created by our aural perception. We have learnt that this phenomenon must never be identified (by name or otherwise) with its physical cause. The 'real' thing, outside our ears, is not a 'tone'. In his *Sensations of Tone* Helmholtz begins by a clear definition of terms, and on pages 4 and 5 of his introduction[1] he attaches exact meanings to 'vibratory motion', 'sensations', and 'perceptions'. The conceptions so expressed he thereafter assumes as being clear in the reader's mind. On the first page of Chapter VI[2] he begins a sentence: 'If we suppose the motion of the air corresponding to the given musical tone to be resolved into a sum of pendular vibrations of air . . .', which expresses his meaning much more precisely and accurately than had he begun: 'If we suppose a complex musical tone to be resolved into its partial tones. . . .' But a little later[3] he finds it simpler to write (of combination tones): 'These tones are heard whenever two musical tones of different pitches are

[1] *Sensations of Tone*, Eng. trans. of 1875. [2] Ibid., p. 174.
[3] Ibid., p. 230.

sounded together, loudly and continuously.' The meaning would be no clearer had he written: 'These tones are heard whenever two pendular vibrations in the air of different frequencies are produced together, with considerable intensities and continuously.' The word 'sounded' in what he wrote is the question-begging word. It corresponds to the words used, naturally and appropriately, by Miss Dorothy L. Sayers, when she wrote of a church bell as 'giving forth her fullest and her noblest note'. We know exactly what she means, and that is what words are for. But in fact the strike-note of the bell, as such, is not given forth by the bell at all; it is produced in our ears by their peculiar nervous mechanism and the way in which it responds to the system of vibrations characteristic of a church bell.

In approaching the relation between acoustics and music from the musical end, the author was precluded from using the procedure employed in a scientific treatise. As his object was gradually to build up new conceptions in the mind of a reader unversed in scientific matters, he could not *begin* with definitions intended to express those conceptions. What course then should he adopt? His own answer was that bridges should not be crossed till we come to them, that meanwhile we can use the licence of which Helmholtz made use on occasion (as in the passage about combination tones quoted above), and that since our approach from the musical end moves in the opposite direction to the approach from the scientific end, the proper place for the present explanation is at the end of this book rather than the beginning.

It is desirable to make this explanation so that the reader, turning back, shall not be confused by the licence employed by the author. When he now reads (p. 14) 'the phonodeik, listening to the sound of a musical instrument', he will interpret it as meaning 'the phonodeik, whose diaphragm is set in motion by the vibrations produced in the air by a musical instrument . . .'. When he now reads (p. 2) 'the highest note we can hear vibrates only a thousand times as rapidly as the lowest note we can hear' he will interpret it as meaning 'the frequency of the most rapid pendular vibration in air that is capable of exciting a response in the sensory apparatus of the ear is only a thousand times that of the slowest pendular vibration capable of exciting a similar response'. But how pedantic and meaningless this phrase would have seemed to the reader had the author used it in the opening essay! Nor

is this all; on occasion an inaccurate phrase such as 'aural illusion' may be more expressive to the non-scientific reader than a reference to a 'perceptual effect'; for analogy with so-called optical illusions suggests a discrepancy between the perception and the perceived object. But the use of 'illusion' in this way is really open to objection: it recalls a ninety-years old controversy between Ohm and Seebeck, of which Helmholtz writes:[1]

'When Ohm stated that it was an "illusion of the ear" to apprehend the upper partial tones wholly or partly as a reinforcement of the prime tone (or rather of the compound tone whose pitch is determined by that of its prime), he certainly used a somewhat incorrect expression, although he meant what was correct, and Seebeck was justified in replying that the ear was the sole judge of auditory sensations, and that the mode in which it apprehended tones ought not to be called an "illusion".'

When he has learnt from these essays to distinguish between the vibration produced in the air by a sounding body (which is a physical occurrence), and the perception produced in the ear and brain by the vibration (which is a musical tone), the reader may find it instructive to translate into correct scientific language the phrases used by the author with less than scientific exactness, not only in the earlier of these essays, but at times in *Music and Sound* (from which any detailed discussion of the psychological factor in hearing was altogether excluded). He could undertake no exercise which would give him a clearer grasp of essentials. For the difficulty is not altogether one of licence in the use of words, which in the examples cited above will be accepted as reasonable. It is even more a difficulty of inadequate terminology; for a complete series of concise terms to express the conceptions we are learning to form is not yet available. The importance of the musical ear in theory about musical acoustics is still too often overlooked; and this appears to be the reason why certain terms are still made to do duty in what is really a variety of meanings. As we have seen, this is particularly true of the word 'tone'.

[1] *Sensations of Tone*, Eng. trans. of 1875, p. 103.

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